Background Considerations

HOW DOES EPISODIC SEDIMENTATION APPLY TO SHELF SANDS AND SANDSTONES?

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The Lyellian legacy implying dominantly uniform, continuous sedimentation over geological time is being replaced by a more punctuated view. Catchy terms like *catastrophic uniformitarianism* are abhorrent because of their semantical obfuscation and because episodic deposition is both geologically common and non-miraculous. Our knowledge of modern environments is biased toward the "normal" condition, however, so we must look to the ancient record for a fuller perspective. Episodic sedimentation results from events whose magnitude deviates significantly from the norm. Both *positive deviations*, such as storms, and *negative deviations*, such as non-deposition, constitute episodes. Of interest here are events recorded at the scale of cores and outcrops; their recurrence frequencies range mostly from decades to millenia. *Recovery time* and *preservation potential* are additional factors critical in assessing the ultimate importance of episodic sedimentation to the rock record. Ancient sandy deposits in epeiric seas illustrate many examples of episodic shelf sedimentation, most of which can be related to modern processes. Clearest *positive deviations* are recorded by thin conglomerate lenses, coquinas, flat-pebble intraclast layers, scoured surfaces, and hummocky stratification. Sporadic graded sandy or shelly beds, rich glauconite lags, alternating unburrowed and bioturbated intervals also reflect episodicity as do polygonal cracks and other emergence features. *Negative deviations* are recorded by hardgrounds (yes, even in sandstone) and/or bored surfaces. Scale, if present, commonly occurs as sharply delineated, thin intercalations within sandstones, indicating repeated deviations from the norm. The volumetrically abundant cross-bedded sandstone facies may provide the most subtle evidence of episodic sedimentation. Dune bed forms in medium-to-coarse sand imply mean current speeds of 80-180 cm/s, which is more than double that typical of modern permanent shelf currents, except at topographic constriction. Many cross-bedded shelf sandstones lack clear evidence of tidal currents, therefore it may be that one of the most common sediments was actively transported only during rare, high-energy events.

WHAT ARE THE FLUID AND SEDIMENT DYNAMICS OF MODERN SHELVES AND THEIR IMPLICATIONS FOR THE ROCK RECORD?

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The wealth of knowledge created by recent studies in physical and geological oceanography has brought us answers, as well as many new questions. However, certain basic concepts seem to be emerging, which can be applied to the study of ancient sediments. About 85% of modern shelves are storm-dominated; 10% are tide-dominated, while sedimentation on the rest is controlled by intruding oceanic currents. Shelf storm currents are combined-flow currents in which a wind-driven, mean-flow component and a high-frequency, wave-orbital current component are subequal in value. They are geostrophic currents, which flow predominantly along the shelf. There is frequently an offshore component of flow near the bottom, but flows at high angles to the shelf contours are infrequent and short-lived. Sustained longshore geostrophic currents during storms are much more important for sediment transport than the relaxation currents dubbed "storm-surge ebb". Hurricanes are not necessarily more effective in sediment transport than mid-latitude cyclones; although they are by definition very intense, many are too localized and rapidly moving to couple efficiently with the shelf water mass.

The origin of shelf stratification is problematic. Ancient shelf sequences frequently contain graded beds with solemarks and a Bouma-like sequence of primary structures, which have been attributed to deposition by density underflows. However, density underflows have not been observed and are considered to be uncommon on theoretical grounds. Geostrophic storm currents, which have been abundantly observed, create beds (tempestites) that are also graded and have Bouma-like primary structures.

Other areas of modern-shelf study that help in our interpretation of ancient deposits are the dynamics of large-scale shelf sand ridges analogous to ancient sand ridge deposits, and studies of Holocene shelf facies patterns analogous to the patterns reported by sequence stratigraphers.

A SPECTRUM OF ANCIENT SHELF SANDSTONES

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A wide variety of processes have operated on the shelves of the world in the past, including waves, storms, permanent currents, subtidal currents and turbidity currents. A variety of sand bodies with different geometrical characteristics has resulted and they commonly contain different sequences of sedimentary structures. On ancient shelves the most common sedimentary structures in sandstones are planar-tangential to planar-tabular cross-beds, horizontal to subhorizontal laminations, current and wave ripples, and bioturbated (>75% burrowed) sandstones. Sequences indicating upward-increasing energy are common on shelves. This sequence may also reflect an increase in grain size, however, it is not unique to shelf sandstones; a similar coarsening-upward pattern is reflected in subsurface log patterns in both river- and wave-dominated deltas and in beach-barrier-dominated shorelines.

Shelf sandstones may be classified on the basis of their position on the shelf (shoreface-attached, inner shelf, middle shelf, outer shelf), and on the basis of whether they are deposited during a transgression, regression, or a stillstand. Both vertical and lateral sequences of lithologies vary with position on the shelf, processes of deposition, and position within transgressive-regressive spectra.

In the middle and outer shelf, shelf sandstones are almost always surrounded by shale. On the inner shelf, and where attached to the shoreface, shelf sandstone overlies a variety of lithotypes (sandstone, siltstone and shale) depending on whether they were deposited during a transgression, regression or stillstand. The lithotypes deposited lateral to shelf sandstones also vary with the position of the sand body within the spectra of transgression-regression. Lateral sequences of lithotypes are most variable in the inner shelf.

Local topography may also affect the distribution of shelf sandstones. Winnowing of topographically high areas may concentrate sand into sand ridges. Shallow depressions in the sea floor from erosion during a fall in sea level, or a retreat of the shoreface, may be filled with coarse to fine-grained sand.

Several of these processes, shelf locations and differing geometrical characteristics are documented for the "Gallup" (Tocito), Shannon, Fales, Hygiene, Teckla and Frontier Sandstones.

Tectonic Control

A TRANSGRESSIVE SAND WAVE COMPLEX IN RELATION TO A PECULIAR STRAIT PALEOGEOGRAPHY: FOLGUEROLES SANDSTONE, MIDDLE TO UPPER EOCENE, SOUTHERN PYRENEES.

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The Folgueroles Sandstone is a Middle to Upper Eocene Formation with a peculiar and very definite sequential and paleogeographic situation at the eastern end of the southern Pyrenean basin. The basin geometry, inherited from a Mesozoic pull-apart pattern, includes a northern active margin (Pyrenean compression) and a southern passive margin (Catalan coastal ranges).

The Eocene fill of the southern Pyrenean basin consists of a succession of five depositional cycles, which are characterized by a stepwise shift of the basin axis to the south (transgressed passive margin) as a response to thrusting in the northern active margin.

A Mediterranean polarity for the third cycle is well documented from the geometry of the sedimentary fill and from the faunal assemblages. The fourth cycle is expansive and seems to have an Atlantic polarity with mixed faunal assemblages. During the transition from the third to fourth cycles, a 10-km wide strait allowed Atlantic-Mediterranean communication. It was then that the Folgueroles sandstone was deposited from reworking of the coastal fans surrounding the southern passive margin (weathered granitic sands). The sandstone body consists of poorly sorted, medium- to coarse-grained glauconitic sands with west-oriented, large-scale trough sets up to 10 m thick, which resulted from sand wave migration. An intricate superposition of stacked sets and erosive surfaces gives a massive appearance without a definite sequential character. It shows a lens geometry with a maximum thickness of 60 m, an observable length of 30 km and a width of 10 km. The estimated volume is about 5 km^3.

The determining conditions for the accumulation of such a massive sandstone body were: 1. sand availability, 2. transgressive conditions, 3. a strait paleogeography with strong and persistent currents, and 4. low rate of subsidence.

GIGANTIC FORESETS INFILLING TECTONICALLY CONTROLLED SCOURS IN THE SHELF FLOOR: AN EXAMPLE FROM THE BOHEMIAN CRETACEOUS BASIN

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Prior to regression of the epeiric sea, the Bohemian Cretaceous Basin was affected by tectonic uplift that caused rejuvenation and erosion in the source area and a large influx of sand onto the muddy shelf. The Cretaceous sand belts of the Intrasudetic Depression (northeastern Bohemian Basin) were deposited along tectonically controlled breaks in slope on the inner shelf floor. These sand belt sequences of Turonian age, underlain, separated by, and interdigitated with shelf mudstone, have been studied along the strike of the sandstone bodies for a distance of about 50 km. The geometry of the sandstone bodies and their internal structure indicate that the initial stage of their formation was due to the infilling of large-scale scours in the shelf floor. Gigantic (exceeding 20 m), steeply cross-bedded units of sandstone, underlain by massive, coarse sandstone with coquina lag deposits were laid down on concave erosional surfaces. As the bodies developed upward, sand became finer and better sorted. Bed forms changed upward in response to a less diversified sea floor topography and low energy regime. Consequently, the gigantic cross-bedded units gave way to sand waves and dunes at the top of the sand belt sequences. Consistent offshore orientation of the gigantic foresets is believed to be related to tectonic control of sea floor topography. The sand waves and dunes were driven both offshore and parallel to the hypothetical shoreline. Numerous examples of sea floor erosion and reversal of paleocurrents (expressed by herrringbone cross-bedding) have been observed. Periodic storm currents superimposed on a tidal current system are the most likely depositional mechanisms in this tectonically controlled basin.

EVOLUTION AND CYCLICITY IN A TECTONICALLY CONTROLLED SHELF. AREN-SANDSTONE, MAESTRICHTIAN, TREMP, SOUTH-CENTRAL PYRENEES.

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The Upper Cretaceous deposits of the Southern Pyrenees (Iberian margin) are localized in pull-apart basins controlled by NE-SW sinistral strike-slip faults. The Aren sandstone extends regionally over 100 km and represents the regressive infill of the Tremp basin. The Maestrichtian sequence (Aren Fm) starts with a basin-wide collapse, which was tectonically triggered. All through the sequence, local folding and faulting produced paleogeographical changes. The sea was open to the north and the shelves extended over a stable southern zone as well as around some unstable and active relief to the east, next to the main NE-SW faults. An unstable shelf developed around the synsedimentary anticline structure of S. Corneli and was subjected to continuous tilting at an angle to the strike of the slope. Major tilting events define depositional cycles characterized by: 1. a reworking phase after the initial tilting, with erosion in the inner area and distribution of sand by longshore drift over the outer shelf; and 2. a shale onlap due to further subsidence. The upbuilding of the Aren sequence results from repetition of such sequences. During the first stages, deposition of successive outer shelf sandstone bodies onlapped the anticlinal structure.

During the second stage, major tilting resulted in a basal erosive surface and coarse siliciclastic influxes, followed by sand distribution. The depositional system includes brackish shale, channel sandstone, aeolian and marine (storm and tidal) reworking and, locally, turbidites. These first two stages are related to the movement of the anticline. A third stage is characterized by stability and beach progradation, as the system was locally tilted by normal faults. The intricate superposition of sandstone bodies through the successive stages of evolution results in an apparent onlap-offlap geometry that would be better interpreted as a fold-controlled uplap.

DYNAMIC EQUILIBRIA IN THE DEPOSITION AND PRESERVATION OF SHELF FACIES

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The deposition and preservation of facies in sedimentary basins is controlled by four general factors: 1. the form of the basin subsidence due to tectonic and eustatic factors; 2. the rate of sediment supply; 3. the type of input source material; and 4. dispersive factors such as wave and tidal energy. We have quantitatively investigated the interrelationship of these factors with a two-dimensional numerical model of basin formation and sedimentation. In this preliminary work, we describe a simple model for sediment dispersion on a storm-dominated shelf. Waves and bottom currents are treated as random variables, producing a dominantly longshore advective transport and a net offshore diffusive transport dependent on water depth, grain size, substrate type, and wind fetch. We have found that the shelf morphology will stabilize under a wide range of input parameters that, characteristically, group into two modes: shelves dominated by allochthonous sedimentation (fluvial source) and those dominated by autochthonous sedimentation (coastal erosion source). Our model indicates, however, that under certain conditions a series of clinoforms can prograde indefinitely, resulting in an ever-widening shelf.

Sediment Source, Supply and Dispersal

ON THE DYNAMICS OF CONTINENTAL SHELF STORM FLOWS

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Storm layer deposits are important sedimentary components formed on continental shelves by waves and semipermanent wind-driven currents. They are prominent in the rock record as well. The structural and textural characteristics of deposits are a function principally of the dynamic conditions existing in the benthic boundary layer both during and after the period of full flow development. Studies of steady-state benthic boundary layer dynamics can provide a better understanding of ancient shelf deposits and paleoceanography. Ekman layers are increasingly recognized as diagnostic features of turbulent benthic boundary layer flows on the shelf, developing during the waning stages of storm activity. Variations in magnitude and direction of the velocity and shear stress vectors with height above the bottom are distinctive; they may or may not be colinear. In an unstratified Ekman layer, the total veering angle or the angular difference between the direction of the bottom shear stress vector, τ_o, and the current, U, above the layer is given in $\sin^2 \alpha_o = 20 (\tau_o/\rho|U^2|)$. Nominal values of boundary layer parameters yield typical veering angles of 10° to 20° in an anticlockwise sense looking downward. With shear stress decreasing upward, a flow carries a suspended load of increasingly larger size grades as the bottom is approached. The result is a selective sorting of the sediment by size away from the source. Structures and textures imparted by the sorting process may be detectable in storm deposits. In a sediment-laden flow, suspended sediment induced stratification effects lead to an increase in the angle of veering with a decrease in the effective bottom stress. Scale analyses suggest a limiting value of $\alpha_o = 90°$; sediment-induced reductions of τ_o greater than 50% have been noted. Information from a numerical model is compared with observations from a shallow, depth-limited Ekman layer. The results indicate the importance of geological observations to an understanding of boundary layer dynamics and to the interpretation of them with respect to sediment distribution. A field study of storm layer deposition dynamics using a new boundary layer profiling instrumentation system is outlined.

SEDIMENT DISPERSAL ON SABLE ISLAND BANK, SCOTIAN SHELF — A STORM-DOMINATED SHELF ENVIRONMENT

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No direct measurements of bottom sediment transport rate, sediment dispersal or the depth of the mobile zone are known to have been made in sands on the outer continental shelves of Canada, yet interpretations of bed mobility have been made without reference to the magnitude or return interval of such events. On Sable Island Bank, interpretations of sand movement have been based on grain size trends, bed form type and orientation, heavy mineral assemblages, and bottom sediment factor analysis. The interpretations suggest that sand migrates in a clockwise fashion around Sable Island, while farther afield, the transport directions appear to be random both in space and time. Recent surveys of sediment mobility on Sable Island Bank suggest that previous interpretations are erroneous. The movement of sediment in water depths greater than 20 m is from the southwest to the northeast in the general direction of the storm tracks, whereas adjacent to Sable Island the transport is predominantly eastwards. The so-called sand waves in the region, used to infer active sediment transport, are indeed shoreface-connected ridges, similar to those observed in the Mid-Atlantic Bight. The significance of such features in terms of sediment mobility and transport direction is quite different from that of sand waves. No active sand waves have been found in the area, although both sand ribbons and moribund two-dimensional megaripples have been found. Circular shell beds, interpreted from side-scan sonograms, indicate a dispersal of shell debris in the down-transport direction. The results of a numeric simulation of sediment transport on Sable Island Bank show that bed load transport takes place almost continuously, but the probability of sediment transport at a given rate decreases with increases in the magnitude of that rate, grain size and water depth. This study indicates that the sediment transport rate at any location can be expressed as a probability density function, and that the return interval of any transport event is defined by that of the major storm events.

CONTINENTAL SHELF SANDS, NORTHWEST GULF OF MEXICO

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The combination of a semi-enclosed sea with a broad shelf, high sediment influx and a wave-dominated energy regime make the northwest Gulf of Mexico unique in North America for studying the processes that have controlled sand occurrence on the continental shelf during the Quaternary. Synthesis of Late Pleistocene/Holocene deposits based on 34 000 km of high resolution seismic reflection profiles plus extensive gravity coring, vibracoring, and grab sampling show that patterns of sand deposition were controlled by glacio-eustatic changes in sea level, paleogeomorphology, and salt tectonism. During low stands of sea level, river courses were incised into the continental shelf and fluvial sands were deposited in alluvial systems comparable in size to the modern Mississippi River. Width of main courses reached 40 km and that of major channels, 8 km. Thickness of sand fill in the ancient channels was as much as 46 m, and grain sizes range from gravelly to silty sand. Deltaic sands accumulated in sediment depocentres along the shelf margin. The five, large, shelf margin deltas of the Late Wisconsinan low stand have been identified. Sequences of distinct high-angle clinoforms (foresets) yielding oblique tangential reflection patterns characterize these deltas. Reworked sands mark both sea level oscillations at the shelf margin and stages in transgression across the shelf. These relict sands represent several environments of deposition: sheets and barriers capping former delta fronts; shoreline sands such as Sabine Bank; and deposits such as Trinity Shoal, which represent reworking of an early lobe of the modern Mississippi delta. Position of streams were determined off Louisiana by active diapiric domes and off Texas by regional southward dip. Continued movement of the diapiric structures caused channel adjustments locally and major diversions of stream courses regionally. Interaction of sediment loading and diapirism at the shelf margin, and beyond, created interdiapiric basins and dams below the shelf margin deltas. These became catchments for sand on the upper continental slope. Modern sand deposition is confined amost entirely to the inner shelf. Thin and irregular, but widespread, Holocene sands found off Texas as far as mid-shelf may be hurricane deposits.

GENERATION OF TRANSGRESSIVE STRATIGRAPHY

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A range of continental shelf sand bodies can be produced when a shoreline transgresses. Four categories of transgression can be recognized, each of which is responsible for producing a characteristic shelf stratigraphy: 1. rapid erosional transgression, which generates a discontinuous stratigraphy of overstepped coastal barriers separated by a thin transgressive veneer; 2. slow erosional transgression, which generates a thin transgressive veneer overlying an unconformity; 3. slow erosional transgression followed by a stillstand, which generates a thin transgressive veneer terminated updip by a fully preserved coastal sequence; and 4. slow depositional transgression during which a variable component of the coastal sequence is incorporated into the shelf stratigraphic record. These four categories are not discrete, but represent intervals of a transgressive spectrum that is governed by sediment supply, regional gradient, relative sea level, wave energy and coastal oceanography. The preservation potential of transgressive stratigraphy is largely governed by the translation path of the shoreface. A simple coastal stratigraphy may consist of a pre-existing substrate, fine-grained backbarrier deposits, sandy barrier deposits and a shelf mud. Horizontal translation of a deep shoreface incises an erosional unconformity into the pre-existing substrate, which is in turn overlain by a sandy lag veneer and a shelf mud. Horizontal and vertical translation of a shallower shoreface leaves the pre-existing substrate intact, preserves: a. part of the backbarrier deposits; b. all of the backbarrier deposits; or c. all the backbarrier deposits plus part of the barrier deposits, overlain by an erosional unconformity, a sandy lag veneer and a shelf mud. Very rapid horizontal and vertical shoreface translation is incapable of reworking the entire shelf retreat path of the coastal zone. In this case, partly reworked segments of the coastal sequence are therefore also incorporated into the shelf stratigraphic record and in turn overlain by a shelf mud. The final stratigraphic sequence results from the horizontal and vertical translation of a shallow shoreface receiving active sediment supply. Under these circumstances the coastal stratigraphy may be preserved intact and erosional unconformities may be absent.

PROVENANCE PATTERNS OF SAND ON CONTINENTAL SHELVES: EVIDENCE FOR DEGREE OF MODIFICATION OF SHELF SANDS BY MODERN SHELF CURRENTS

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After six years of studying the provenance of sands on eastern and southern U.S. shelves, we conclude that sand provenance patterns observed on these shelves reflect the late Pleistocene paleogeography of the shelves, and have for the most part been undisturbed by modern shelf currents. Three examples are offered to illustrate this idea. The first deals with the provenance of sand on the southern New England shelf. It will be shown that the distribution of glacial sands on this shelf coincides with the location of the late Pleistocene glacial deposits, while the distribution of fluvial sands follows the traces of relict stream systems. The second example comes from the South Texas shelf, where two sand types, mature multicyclic sands and immature first cycle sands, are found in modern nearshore and ancient shelf deposits. The sands of the modern Guadalupe River are dominated by the mature sand type while those of the modern Rio Grande and Colorado are dominated by the immature sand type. During the Pleistocene, these rivers deposited sand in what are now relict deltas and river valleys on the outer shelf. The sands overlying the relict Colorado and Rio Grande deltas are, like their modern counterparts, enriched in first-cycle sands, whereas those overlying the ancestral Guadalupe River valley are enriched in multicyclic sands. The last example is taken from the Georgia Bight, where two sand types, highly reworked coastal plain sands and less reworked fluvial sands derived from the Piedmont, are found in the shelf sediments. The Piedmont sands are found in abundance in a series of coast-perpendicular strips, which run from the shore to the shelf edge and which coincide with the trends of Pleistocene stream systems that crossed this shelf during lowstands. These three studies illustrate the point that the patterns of sand provenance types on the eastern U.S. and northern Gulf of Mexico shelves are mostly controlled by the late Pleistocene paleogeography of these shelves and have undergone little net movement, which would have obscured these patterns. The preservation of such well defined provenance patterns seems to contradict physical measurements of bottom currents, suggesting major transport of sand on these shelves.

SEDIMENT PATTERNS RESULTING FROM LIQUEFACTION OF A SHELF SAND BODY

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A large magnitude earthquake ($M \sim 7$) occurred on November 8, 1980, 60 km off the coast of northern California. Damage was minimal onshore, but extensive changes to the sea floor were reported from the area of the Klamath River delta. Data from three successive surveys conducted in the area at intervals of

one, six, and eleven months after the shock demonstrate the extent and type of sea floor failure. Side-scan sonar and high-resolution seismic reflection profiles, together with sea floor photographs and video images, define a thin (<15 m) failure zone that measures 1 × 20 km and trends parallel to the shoreline on the shallow (~60 m) and nearly flat (~0.25°) surface of the Klamath River delta. The failure zone is characterized by a very flat terrace (~0.02°), which is mantled by silty sand and is bounded seaward by an irregular 1-to 2-m high scarp.
Sonographs and photographs of the sea floor show that failure occurred by liquefaction and sediment flow, producing a variety of sediment patterns and relief features on the sea floor. Failure by liquefaction is inferred based on: 1. a seaward thickening of the failure deposit; 2. sand boils 5 to 25 m in diameter; 3. the presence of a prominent, nearly continuous, blocky, chaotic scarp at the seaward terminus of the failure zone; and 4. belts of small (10 m long, 0.5 m high) pressure ridges seaward of the scarp. These features indicate sand was mobilized into a flow. In addition, individual flows extended across the terminus of the failure, and overlapping flow deposits became more irregular in a seaward direction as the flows became progressively less mobile.

THE BIRD FIORD FORMATION: A SPECTRUM OF SHELF ENVIRONMENTS

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The Middle to Upper Devonian Bird Fiord Formation, a constituent formation of the Franklinian Geosyncline, Canadian Arctic Islands, displays considerable vertical and lateral facies variation. On southwest Ellesmere Island, five informally defined members represent 1. a basal sabkha setting, 2. a carbonate-dominated shelf, 3. a clastic-dominated shelf, 4. deltaic/clastic shelf interdigitation, and 5. fluvial-deltaic environments. The change from carbonate to clastic lithology is associated with the onset of deltaic sedimentation, however, shelf processes redistributed distal deltaic sediments into sheet-like layers. Extensive cliff exposures permit examination of shelf lithofacies and their sequences. Broad (?tidal) channels, low-amplitude bar forms, small-scale scour surfaces and abundant rippling attest to distribution of sediment by active currents.
Delta encroachment is indicated by the introduction of extensive noncalcareous, cross-bedded, proximal mouth-bar sandstones interbedded with bioclastic shelf sequences. These mouth-bar deposits are lensoid in cliff section; their tops commonly display evidence of reworking by shelf processes. Further advance of the delta is indicated by an upward increase in non-calcareous, cross-bedded sandstones and the occurrence of well defined distributary channels. The uppermost member of the formation consists of stacked channel sequences, which probably represent a braided stream environment.
The lower carbonate members are absent on Grinnell Peninsula (Devon Island), Cornwallis and Bathurst Islands. In these areas, a spectrum of shallow clastic shelf and interface environments (barrier island, tidal channel, lagoon, distributary channel and interdistributary bay) occur in the Bird Fiord Formation transition from carbonates of the underlying Blue Fiord Formation to the deltaic environments of the overlying Okse Bay Group.

ASYMMETRY OF FORM AND LITHOLOGY, LATE CRETACEOUS SHELF SANDSTONE COMPLEXES, HOUSE CREEK AND HARTZOG DRAW FIELDS, POWDER RIVER BASIN, WYOMING

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The Sussex Sandstone at House Creek and the older Shannon Sandstone at Hartzog Draw fields, have been interpreted as thicker, relatively sandy parts within extensive far-offshore shelf sandstone and shale complexes. The complexes were deposited on broad depositional shelves in the early Campanian seaway and are now enclosed in the marine Cody Shale. Exact limits of the complexes are uncertain. Shale and thin-bedded sandstone are relatively widespread within the complexes. Mappable sandy bodies in the field areas are about 30 to 50 km long and perhaps up to 25 km wide. Thicker parts containing cross-bedded sandsone form elongate bodies trending about 30°NW at Hartzog Draw and House Creek. Maximum thickness ranges from about 15 m at House Creek to 26 km at Hartzog Draw. Overall shape of the thicker parts is plano-convex upward in cross-section and ellipsoidal in plan; thinning is relatively rapid on the northeastern flanks, which are also relatively straight. General slopes on the flanks of the complexes, estimated from isopach maps, were very slight; relatively steep slopes on the northeastern flanks were probably a fraction of one degree. Lithological variation within the thicker parts of the complexes also displays asymmetry; sandstone on the southwestern flanks is finer grained, relatively shaley, thinner bedded and grades laterally into the more extensive shaly sandstone. In the field sequences, shaley sandstone separates silty and sandy Cody Shale below from cross-bedded sandstone above. Lower parts of the cross-bedded sandstone are relatively variable, forming the lower part of a sanding-upward sequence. The cross-bedded sandstone is capped by thin, bioturbated, silty sandstone or burrowed sandstone. The transition zone in the lower part is much thicker than that in the upper, resulting in vertical asymmetry. Lateral asymmetry at House Creek field is expressed statistically with wireline log data. Cross-bedding vectors from oriented cores at Hartzog Draw indicate a southerly transport direction; hence steeper slopes and relatively well developed cross-bedded sandstone appear to characterize the left sides of the complexes when viewed down current.

CHARACTERISTICS OF SHOREFACE-CONNECTED RIDGES, SABLE ISLAND BANK, NOVA SCOTIA

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Examination of recent bathymetric, side-scan sonar and high-resolution seismic data shows that Sable Island and its east and west extensions are surrounded by shoreface-connected ridges. The main ridge field to the south and west of the island contains 80 ridges in water depths of 16 to 40 m. These ridges have an average height, spacing and length of 5.1 m, 1700 m and 8 to 10 km, respectively, and locally occur in a heirarchically superimposed arrangement. Only six ridges occur to the north of the island in water depth of 10 to 25 m. Their average height, spacing and length are 3.8 m, 1900 m and 5 km, respectively. All ridges converge eastward on the shoreline with angles of 70° south of the island and 35° on the north. The smaller ridge sizes, shallower depths and smaller angles of divergence on the north side are probably due to the lower wave energy in this area. The ridges appear to be asymmetric with their steeper face to the west or northwest, but the maximum local slope is generally on the eastern flank (2.1° east versus 1.1° west). The western flank of the ridges is acoustically reflective and is interpreted as being mantled by coarse lag material that represents the top of the Pleistocene. Smaller bed forms, including wave ripples, and two- and three-dimensional megaripples less than 1 m high, can be identified on this surface. The megaripples indicate shoreward flow parallel to the ridge axes. Seismic data show that the ridges are partially erosional and partially constructional. The geometry of the Pleistocene surface beneath the ridges suggests an overall eastward movement of the ridges, probably in response to the combined effects of tidal currents and wave-generated currents associated with northeast-tracking winter storms.
Vibracores collected in 23 to 27 m of water show that the depositional parts of the ridges consist of 2 to 6 cm thick beds in medium to coarse, dominantly quartz, sand, with limited amounts of shelly debris. The majority of the beds are inversely graded, and are organized into coarsening-upward sequences 30 to 90 cm thick. Cross-bedding has not been identified. The uppermost 10 to 20 cm of each core is generally bioturbated more intensely than the remainder of the core. Conceptual models of ridge evolution predict either coarsening- or fining-upward sequences through the ridges.

SEA FLOOR DYNAMICS ON THE LABRADOR SHELF

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Recent geological-geophysical studies of the Labrador Shelf demonstrate very dynamic bottom conditions over 70% of the shelf area and extending to depths of 230 m. A variety of sediment reworking processes that affect the sea floor are described, but the most important agent — iceberg scouring — is emphasized. A series of oriented bottom photographs (colour) taken every 14 m along a 6 km transect show a clearly defined "fresh" keel mark cut through a lag gravel and into the underlying gravelly, silty-clay substrate of Makkovik Bank. Transects taken from Saglek and Nain Banks in similar water depths ranging between 140 and 160 m also showed one "fresh" keel mark per 6 km of sea floor photographed. On Saglek Bank, a detailed synthesis of high resolution acoustic data, side-scan sonar and age determinations from piston core samples suggest complete iceberg reworking of all shelf areas shallower than 152 m within the last 10 000 years. Another important dynamic process on the shallow (< 165 m) areas of the shelf is winnowing by bottom currents. This process has produced a well developed lag gravel overlying the gravelly, silty-clay substrate. The presence of sharp-crested sand waves and stringers migrating across the sea bed in some places indicates a contemporary current regime strong enough to develop the lag surface. Photographic evidence also indicates rapid winnowing of the "fresh" scour marks. The evidence for strong current winnowing and the clearly defined keel marks suggest that "fresh" may represent days or months. The recurrence interval of modern iceberg scouring on the Labrador Shelf could be determined by measuring the rate of scour degradation by current winnowing for a given area and relating the number of partially degraded scours of a known age to the number of fresh scours within the same area. It appears that in shallow areas there is an erosional setting with only a limited supply of mobile sediment available due to the effective armouring by the lag deposit. However, dissection of the lag surface by modern grounded icebergs does expose the substrate to the winnowing process, thereby generating some additional sediment. Contemporary deposition is mainly limited to depths > 300 m in the transverse saddles, the marginal trough and shelf edge. Additional, but relatively minor, processes affecting the sea bottom are: ice-rafting, reworking by macrobenthos and slumping.

SANTA CLARA RIVER DELTA, CALIFORNIA: SEDIMENT SUPPLY AND TRANSPORT

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The Santa Clara River is the largest source of detrital sediment supplying the coast of the California Borderland. During the last 50 years, the average annual sediment supply was about 3.5×10^6 metric tons. However, in the semiarid climate of southern California, about half of the total supply occurred during 1941 and 1969, the two years of high rainfall. Due to the direct approach of waves from the west, and the prevailing longshore drift toward the south, the average supply of 1×10^6 metric tons of sand and gravel is transported away from the river mouth within one year. During 1941 and 1969, the higher rates of sediment supply resulted in the formation of a subaereal delta on the shelf, adjacent to the Santa Clara River mouth. For example, the maximum rate of supply for one 24 h period in 1969 exceeded 22×10^6 metric tons. A repetitive series of bathymetric surveys permits delineation of the rates of erosion and transport of delta sediments following the 1941 and 1969 events. In the area of maximum deposition, sediments deposited at a depth of less than 12 m following a major flood are removed within several years. However, remnants of the delta were present at a depth of 30 m for more than 20 years after the 1941 influx of material. Bottom current speeds of 15 to 30 cm/s on the inner shelf are significantly influenced by tidal currents. Transport of eroded deltaic sediments occurs in an offshore as well as an alongshore direction. Some of the sediment transported to the south on the inner shelf enter Hueneme Canyon, which serves as a conduit for transport of coarse-grained material into deeper water. Additional information from beach profiles, surficial sediment samples and analysis of vibracores in the vicinity of the delta and adjacent shelf provide detailed documentation of the pathways of transport for sediments deposited from episodic floods and subsequently reworked by wave and current action.

SEDIMENTARY SETTING AND CHARACTER OF SAND AND GRAVEL BED FORMS ON THE OPEN CONTINENTAL SHELF OFF WESTERN CANADA — STATUS OF KNOWLEDGE

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Sand and gravel were deposited on the shelf primarily during the Pleistocene glaciations of the mainland and outer islands. Relatively little sediment has been introduced to the shelf since, and most of this has consisted of silt and clay. The proportion of sand and gravel can be highly variable, even on comparably deep parts of the shelf. This is in part a reflection of original differences in the character of sediment supplied to the shelf. It may also reflect non-uniform isostatic depression of the shelf by Pleistocene ice. Variable depression could have exposed what are now comparably deep parts of the shelf to different wave and current intensities at the time of the last sea level minimum. The present wave regime of the shelf is characterized by peak storm wave periods as high as 17 to 20 s and maximum probable wave heights, which can exceed 17 m, but are ≤5 m 90% of the time. Surface tidal currents generally do not exceed 50 cm/s. The major sand and/or gravel bed forms that have been recognized to date are ripples, waves and patches. Most, if not all, of these features are generated by prevailing oceanographic processes. Combined flow (wave- and current-generated) ripples have been observed in medium- to fine-grained foraminifer-rich sands as deep as 130 m. Linguoid current ripples and asymmetric waves (~40 m wave length; 2 to 3 m wave height) are evident in shelly sand at 40 and 90 m respectively, where surface current velocities can exceed 150 cm/s in the vicinity of passages between small islands on a shelf bank. Symmetric waves up to 50 cm high with wave lengths of up to 1.5 m in coarse shelly sand at a depth of 80 to 105 m, and gravel waves 1.5 m high with wave lengths of 4 to 5 m at a depth of 40 to 60 m are being generated by storm swells originating from the southwest. Sand patches with a thickness of 2 m or less and variable width extend for >1 km at a depth of 60 to 70 m. They are nestled in gravel and are oriented transversely or longitudinally to the present long axis of the local tidal current ellipse.

THE SHELF SEDIMENT WEDGE OFF THE SOUTH AND EAST COASTS OF SOUTH AFRICA.

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The Holocene shelf sediment wedge has been elucidated by high resolution seismic reflection profiling augmented by side-scan sonar imagery, box cores and grab samples. The quasi-continuous sediment wedge extends over 1500 km from the narrow east coast shelf (12 km) to the broad south coast shelf (100 km). The wedge varies in width from 4 km up to 35 km, while thicknesses can be up to 40 m. The wedge lies on a gently-dipping erosion surface which truncates folded Tertiary and Cretaceous strata and is frequently incised by channels. The inner margin may be banked against steep coastal cliffs, merge with shoreface sands or be flanked locally by nearshore rocky outcrops. The water depth of the outer margin can be up to 100 m and may be draped in mud, dammed by Pleistocene aeolianite dune ridges, or flanked by geostrophic current-generated bed forms on the mid-shelf of the east coast. These large bed forms are sometimes superimposed on the wedge, and in other cases, starved bed forms lie seaward of the main sediment wedge. Whereas a single complex dune cordon occurs on the east coast, multiple aeolianite ridges interfere with the sediment prism on the south coast. In both areas relict sediments lie seaward of Holocene sediments, except where the wedge locally reaches the shelf edge near Port St. Johns. Locally near headlands, embayments or coastal offsets, where bed load sediments converge in sediment traps, submerged spit bars form at water depths of 40 to 90 m within the wedge. Sediments with these features are partly derived from longshore drift and are texturally and compositionally similar to adjacent beach sediments. Large progradational cross-beds seen in seismic profiles and small cross-beds seen in box cores characterize these features. Mud-draped sand bodies, such as the Robberg submerged spit bar that exhibits acoustic anomalies suggestive of gas accumulation, may provide potential hydrocarbon reservoirs. Narrow linear sand bodies, such as those that extend along the South Africa shelf and include submerged spit bars, may be mistaken in the fossil record for shoreface sands including beaches, sub-aerial spits and shallow bars. We suggest that a drowned sand body in the Norwegian Sea, which has been interpreted as a beach, may be a submerged fossil spit bar.

AEOLIAN DELIVERY OF SAND TO PRE-SILURIAN STABLE SHELVES RESOLVES APPARENT PARADOXICAL OCCURRENCE OF TRANSGRESSIVE SHEET SANDS

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Dake (1921) hypothesized that, prior to the mid-Silurian establishment of soil-binding land plants, wind must have been an important transport mode for sands and silts. Cotter (1978) has interpreted the absence of pre-mid-Silurian meandering fluvial deposits to be the result of the absence of soil-binding plants, which dictate a braided style for fluvial processes. A natural consequence of this is to assume that accumulation of pre-Silurian shelf sands may be, at least in part, the result of the offshore accumulation of wind-blown sand. Recent analogues, and the results of physical experiments, indicate that this mechanism could account for the entire accumulation of such a sandstone as the St. Peter in terms of rate of deposition. An analysis of the morphology of quartz grains (using Fourier and SEM techniques) from samples from the St. Peter Sandstone supports this conclusion.

Acceptance of such an origin for St. Peter-like blanket sandstone, resolves the apparent paradox of deposition of relatively thick sheet-like sands on a stable craton during marine transgression — a mode of deposit not observed on present-day stable continental shelves. An aeolian interpretation of St. Peter-like sandstones implicitly carries with it a prediction of the size and location of areal thickness variations: 1. the deposit should be thickest in the vicinity of the low-stand shoreline; 2. large local changes in thickness will be most pronounced near the highstand shoreline because of erosion/karstification of the unconformable substrate; and 3. the relation of shoreline orientation to prevailing wind direction should play a major role in producing intermediate-scale thickness variations.

SOURCES, DISTRIBUTION AND MIXING OF LATE PLEISTOCENE AND HOLOCENE SANDS ON THE SOUTH TEXAS CONTINENTAL SHELF

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Grain shape and mineralogical analyses were used to determine the sources of sands on the South Texas shelf. Two grain shape types were found in the sands using the Fourier grain shape technique. One type, associated with sands rich in igneous and metamorphic rock fragments and quartz varieties as well as feldspars, is considered to represent first-cycle sands eroded from igneous and metamorphic rocks of the Llano Region and of West Texas and New Mexico. The second type, associated with sands rich in sedimentary quartz and sedimentary rock fragments, represents sand eroded from the Texas Coastal Plain and High Plain. Variations in the proportions of these sand types in the nearshore sediments reflect both the changing sources of nearshore sand and their transport and mixing by nearshore processes. Three sedimentary provinces, corresponding to those defined by heavy mineralogy, are defined on the basis of their content of first- and multi-cyclic sand. Modern sands of the Rio Grande Province are derived from the drainage basin of the Rio Grande and contain high proportions of first cycle sand; such sands are found in the nearshore zone between the Rio Grande and the 27° latitude line to the north of the river mouth. Modern sands of the Texas Coast Province are reworked deposits of the coastal plain rivers and are dominated by multicyclic sands. Such sands are presently transported southwestwards by longshore currents to the 27° line where they converge with northward-transported Rio Grande sands. Modern sands of the Western Gulf Provinces come from the drainage basin of the Colorado River and contain high proportions of first-cycle sand; such sands are also transported toward the southwest, where they are gradually diluted by Texas Coast Province sands. Ancient sands of these provinces are also found in relict deltaic deposits on the outer shelf. Previous studies had considered the southernmost outer shelf deltaic sands to be of the Rio Grande Province, and our data agrees with this. However, previous studies had considered the northernmost outer shelf deltaic sand to be only of the Western Gulf Province, but our data reveals that to the west of the relict Colorado delta these sands belong to the Texas Coast Province. Seismic data supports this conclusion by showing that these outer shelf sands of the Texas Coastal Province overlie coastal plain river valleys.

SAND SHEETS AND SAND RIDGES: THE IMPORTANCE OF SEA LEVEL CHANGE

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On modern non-tidal shelves, where there is active fluvial sediment supply, the sand-dominated zone is generally only a few tens of kilometres wide (e.g. shelves north of the Columbia River and west of the Rhône). Wider, sandy shelves have negligible fluvial supply (e.g. eastern U.S.A. shelf, Spanish Saharan shelf). If there is sediment supply and a stable shoreline position, a narrow sand accumulation is expected, and if there is negligible supply, reworking of previously deposited sands results. The emplacement of sand on wide modern shelves beyond the present coastal zone appears to have been at times of lower sea level. Absence of mudstone from broad tracts of sandstone requires fluctuations of shoreline position in this scenario. (Either the mudstone was deposited but was then removed by reworking as sea level fell, or it was not deposited because rate of sediment input was low. In the latter case, formation of the sand accumulation required migration of the coastal zone where sand is deposited.) Sand deposits are formed in the coastal (including braided stream plain) and shallow marine (<40 m) zones which migrate in response to relative changes of sea level. The bed forms created in this zone are often ridges oblique to the shoreline. In areas where waves and wind-driven currents are opposed (but tidal currents are weak) shoreface-connected ridges are formed and left behind by a rise in sea level (e.g. eastern U.S.A. shelf, Argentine shelf). On tidal shelves where currents are strong (>1 m/s) oblique ridges form part of systems of parabolic sand banks, which give place to parallel linear sand banks farther offshore. It is proposed that the parallel linear sand banks grow from the parabolic banks which are left offshore during a rise in sea level. Thus the formation of some large parallel sand banks is seen as a consequence of a rise in sea level. (There are other parallel sand banks formed in embayments and on shelf edges where different mechanisms prevail.) Tidal shelves with weaker currents (0.6 to 0.9 m/s) display sand waves which, in the best documented case (the southern North Sea) are reworking a sand sheet emplaced at low sea level.

ACCUMULATION OF SAND AND MUD IN ACCRETIONARY SHELF ENVIRONMENTS

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For accretionary shelves, sediment accumulation largely depends on the amount and type of sediment supplied. On a worldwide basis, the largest sources of sediment to shelves are rivers. Other sources (in particular, glacial, biogenic, coastal) may be locally important for sediment supply. Shelves generally have a basal sand layer, which formed during the Holocene transgression, and on which more recent fluvial sediment has accumulated. The sediment discharge of most rivers is greater than 75% mud. Sediment accumulation associated with large fluvial sources ($>10^8$ metric tons/yr) is characterized by inner-shelf mud deposits and the accumulation associated with smaller sources is characterized by mid-shelf mud deposits. Physical processes (primarily surface waves) inhibit net accumulation of mud on inner shelves, and prevent accumulation where fluxes of mud are small. In the latter case, sand accumulates from fluvial sources and the retreat of the coast. Mud deposits overlie the transgressive sand layer, whose surface may be plain or built into bed forms (e.g., sand waves). This interface between mud and sand is commonly transitional due to the mixing of mud and sand within a surface layer of the sea bed (surface mixed layer) during the embryonic stages of mud deposit formation. Modern sand accumulates within mud deposits and shows a distinct depletion along dispersal systems. In proximal regions of large dispersal systems ($>10^8$ tons/yr), biological mixing is negligible and sediment accumulation is rapid (>2 cm/yr), therefore sand is preserved as interlaminae and interbeds within the mud deposit. In small dispersal systems, biological mixing occurs and sediment accumulation is slow (<1 cm/yr), therefore sand and mud are homogenized before preservation. Distal regions of all dispersal systems contain little sand, because of its preferential accumulation in proximal regions. Within the muddy, distal portions of dispersal systems, progressive fining is not observed, probably because particles are transported as aggregates.

CURRENT-DOMINATED SEDIMENTATION IN THE NORTHEASTERN CHUKCHI SEA, ALASKA.

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The Chukchi Sea is a broad, shallow (<60 m deep), essentially nontidal (tidal range <10 cm), epicontinental sea that is ice covered 8 to 9 months of the year. A northward-flowing coastal current (velocity ± 200 cm/s) apparently controls the sediment distribution and texture along the east side of the sea. Extensive surficial gravel lag deposits, gravel-sand ribbons, sand-wave fields, and sandbanks record areas of erosion and deposition as well as sea bed processes within this current-dominated part of the northeastern Chukchi Sea. Reconnaissance investigations along the east boundary of the coastal current, using side-scan sonar, high resolution bathymetric and seismic profiles, television observations, and sediment sampling, define the major sea bed features, sediment pathways, and areas of sediment deposition. Sediment input to the coastal region is low, and over much of the sea floor a thin sediment cover of sand and gravel overlies bedrock. Two capes represent the major sediment depocentres. Arcuate sandbanks covered with sand waves, which may exhibit the same or opposed orientations on the ridge flanks, form off one cape where the coastal current is far offshore. These sand banks migrate seaward, where ice groundings and the coastal current erode the sediment and form fields of northward-migrating sand waves. Where the coastal current approaches the shore, gravel-sand ribbons oriented parallel to the shore or fields of northward-migrating sand waves form. These sand-wave fields are more than 30 km long and are elongate parallel to the coast; the bed forms are 1 to 3 m high oriented normal to the coastal current trend. The sand bodies that form as a result of sediment transport and deposition within the coastal current are as much as 10 to 12 m thick.

EXAMPLES OF CONTRASTING DEPOSITIONAL FORMATS OF SHELF-TO-BASIN TRANSITION FROM THE COLORADO AND MONTANA GROUPS (CRETACEOUS) OF SASKATCHEWAN AND MANITOBA

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The marine strata of the Colorado and Montana Groups (Middle Albian to Campanian) of Saskatchewan and Manitoba were laid down on two shelf areas, which were the sites of sand and silt sedimentation. They were separated by a basin proper, where mainly mud was deposited. A rapidly subsiding western shelf received abundant sand and silt from the Cordillera to the west, whereas a relatively quiescent eastern shelf from the adjacent Shield received comparatively minor amounts of sand. Ubiquitous sandstone-mudstone couplets, up to a few centimetres thick and characterized by current markings on the sandstone soles, and simple grading of different types of detritus (siliciclastic grains, fish-skeletal debris, *Inoceramus* prisms), are evidence for the widespread influence of storm-surge generated suspension currents as agents of sediment dispersal. Two main regressive-transgressive events are suggested by prominent northeastward-thinning sandstone wedges, formed on the western shelf and enveloped in basin mudstones: the Bow Island-Viking succession (Colorado Group) and the Belly River sequence and associated tongues (Montana Group). Nearshore/shoreline, proximal-shelf and distal-shelf environments are distinguished in the former on the basis of lithology, sedimentary structures and trace fossils, whereas limited data permit only recognition of a generalized shelf facies in the latter. Clinobeds, delineated by bentonitic mudstones in the Viking Formation of western Saskatchewan, are considered to have originated as tidal sand ridges. The Ashville Sand of southern Manitoba was deposited on the eastern shelf as a widespread blanket facies and a localized "trough" facies. Trough initiation may have been a result of differential compaction of the underlying strata across a belt of erosional irregularities at the sub-Mesozoic unconformity. A similar origin is postulated for parts of the Viking-Newcastle succession, which is approximately equivalent and exhibits a pronounced variation in thickness and overall westward thinning across southeastern Saskatchewan. Sand dispersal across both shelf areas was influenced by basement structure, solution-generated collapse features associated with the Middle Devonian Prairie Evaporite, and compaction-formed surface irregularities.

SEDIMENTOLOGY OF SAND SHOALS ON THE LOUISIANA CONTINENTAL SHELF

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More than 1000 km of high-resolution seismic profiles correlated with seventeen 10 to 12 m vibracores provide the data base for analyzing the sedimentological characteristics of transgressive sand shoals on the Louisiana continental shelf. The development of these shoals is initiated by abandonment of older Holocene complexes of the Mississippi delta, followed by a subsidence-induced rise in sea level. Ship and Trinity Shoals are the largest of these shelf sand bodies and provide a possible modern analogue for some Cretaceous shelf sandstones of the Western Interior.

The Ship Shoal sand lies disconformably on the deltaic muds of the Maringouin complex, abandoned some 6150 years B.P. The shoal is asymmetric landward, 32 km long, and 2 to 4 km wide. Relief ranges from 2 to 6 m from east to west, with a corresponding decrease in water depth over the shoal crest from -6 to -3 m. Maximum sand body thickness is 7 m in the western region, pinching out seaward on the erosional inner shelf and terminated landward by a depositional surface. Internally, the shoal is characterized by very low-angle, landward-dipping clinoforms, while the underlying deltaic sequence contains low-angle, seaward dipping clinoforms. Numerous small channels occur below the shoal in the western area, although no large channels were seen on seismic profiles. Cores show a 3 to 7 m thick, coarsening upward sequence of fine grained sand and shell, overlying a dark, organic rich, silty clay with numerous wavy and lenticular interbeds of silt; burrowing is very rare.

Trinity Shoal is associated with the Teche complex, abandoned some 3500 years B.P. The shoal is a lunate, shore-parallel feature some 36 km long and 5 to 10 km wide. Relief ranges east-west from 2 to 3 m, with a corresponding decrease east-west in water depth over the shoal crest from -5 to -2 m. The Trinity Shoal sand body is 5 to 7 m thick, and is composed internally of a set of low-angle, westward dipping clinoform reflectors. Three levels of channeling that related to sea level changes in the Early Wisconsinan, Late Wisconsinan, and Holocene (Maringouin delta) underlie and occur seaward of Trinity Shoal. Continued sedimentation of the modern Atchafalaya Delta will soon encase Trinity Shoal in mud.

Storm-Dominated Shelves

CONSTRAINTS ON THE PALEOHYDRAULIC SIGNIFICANCE OF HUMMOCKY BEDDING

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The dimensions of low-steepness bed forms found in ancient marine sequences are used to test three fluid mechanical hypotheses. The first is that they are formed under purely oscillatory flows generated by the passage of progressive gravity waves. The second is that hummocky bed forms are similar to supercritical bed forms (such as three-dimensional antidunes) under a purely unidirectional flow. The third hypothesis is that hummocks are produced by the combined action of oscillatory and unidirectional shear flows, such as gravity waves superimposed on a gradient current related to storm set-up. Preliminary analyses indicate that the first hypothesis is the least likely, based essentially on the incompatibility of observed hummock spacing and possible values of the ratio α/λ under waves (where α is the amplitude of oscillation near the bed and λ is the bed form spacing). An origin beneath standing surface waves causing a spatially periodic near-bed mass transport is an alternative. For the second hypothesis, the origin of the density interface that acts as an internal wave is problematical, and the preservation of well defined laminae is inconsistent with an origin under antidunes. The third hypothesis of combined flows is the most probable. However, formation of hummocks under vigorous storm return flows is unlikely since the bed planation threshold would be over-reached even without the enhancement of bottom shear stress due to waves. If hummocky cross-stratification is formed in water depths of up to 80 m (Dott and Bourgeois, 1982), any superimposed waves are most likely to have been moderate in period, more characteristic of waning storm conditions combined with sluggish to moderate storm surge gradient currents. The implication is that the interpretation of hummocky bedding as formed on the shoreface solely by the action of progressive storm waves should be treated with considerable scepticism.

WAVE-DOMINATED SHELVES: A MODEL OF SAND RIDGE FORMATION BY PROGRESSIVE INFRAGRAVITY WAVES

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Sand ridges with longitudinal crests that have spacings of hundreds to thousands of metres have been observed forming on sandy shelves. The stability of these sand bodies suggests that they may be time-averaged responses to the complex hydrodynamics of their environment. Consideration of the scales involved seems to indicate that locally-generated storm waves are not responsible for these structures. Such disturbances may indeed modify existing bars, but do not appear to contribute essentially to the formation and mean features of sand ridges on many shelves. On the shelves that we shall refer to as "wave-dominated", a mechanism that may account for systems of sand ridges is associated with infragravity waves (waves with periods of 0.5 to 5 min). A description of the formation of bars on shelves by the propagation of infragravity waves is outlined. The surface hydrodynamics is modelled by the nonlinear dispersive shallow-water theory. The wave-induced flux of sediment is calculated using the mass-transport velocity. The bed topography is then described using a continuity equation. This theoretical description results in a coupled system of nonlinear partial differential equations. This system may be simplified somewhat by using a model decomposition of the surface wave. The resulting equations are then approximated numerically in order to make quantitative predictions about field situations. The model has been tested against *in situ* measurements made on the Atlantic coast of the U.S.A. (the Delmarva and Virginia coastal shelves). The agreement between the predictions and the measurements was sufficiently good to warrant some confidence in the mechanism inherent in the model's derivation. Specifically, the successive crest-to-crest distances, which in the model depend only on the mean bed slope and the incident wave conditions, agree quite well with measured values. The very long time required for the formation of fully-developed bars provides an *a posteriori* indication of the stability of these structures. Moreover, general trends in the onshore transport, and slow ridge migration due to shore retreat can also be predicted using this model.

PALEOHYDRAULIC SIGNIFICANCE OF HUMMOCKY STRATIFICATION

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The distinctive characteristics of hummocky stratification are: 1. erosional lower bounding surfaces (of laminasets) with typical slope angles of less than 10°; 2. laminae parallel or subparallel to the lower bounding surface and scattered dip directions of laminae; 3. laminae thickening into swales; and 4. irregularly spaced swales and intervening hummocks at intervals of one to several metres with a relief mostly of 5 to 30 cm. Commonly, hummocky-laminated beds alternate with bioturbated strata. Hummocky stratification is usually found in fine-grained sandstone located stratigraphically between offshore and shoreface deposits, and it has been linked genetically to storm-wave processes. There remain major questions concerning the paleohydraulic significance of hummocky stratification, particularly whether it is produced by random scour and drape, or by regular bed-form development. Hummocky stratification is not a ripple-scale phenomenon (see 4, above); ripples, controlled by the mean saltation length or by the orbital diameter of the wave, if this is smaller, are 5 to 20 cm in wavelength in fine sand. Larger bed forms, controlled by orbital diameter alone, could exist, but the time necessary to build a dune of the dimensions cited above is apparently greater than one wave period. Most critically, there is no microstratigraphic evidence for regular migration of bed forms, nor for regular scaling in the geometry of the laminae. We propose that hummocky stratification is a scour-and-drape phenomenon with the following controls: wave conditions must be sufficient to produce properly scaled scours (swales); waves must be breaking nearby in order to produce the large fluxes of suspended sediment that supply the drapes, and there must be a local convergence in the sediment-transport field so that deposition will occur. These conditions are met seaward of the offshore bar during severe storms. Detailed stratigraphic analyses employed in conjunction with models for flow processes in this environment can lead to estimates of paleohydraulic conditions.

STORM-AND WAVE-DOMINATED SANDSTONES ON AN EXTENSIVE ORDOVICIAN SHELF

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The Monte da Sombadeira Formation is a sequence of storm- and wave-affected sandstones (15 to 190 m thick) interbedded with, and lying between "shelf" mudstones. The formation can be recognized throughout central Iberia, and outcrops have been studied in an area of over 40 000 km^2. Hummocky cross-stratification (HCS) is common throughout the whole outcrop area, but proximal and distal facies may be distinguished. The most proximal facies (?shoreface) has amalgamated HCS within a continuous sandstone sequence. Another proximal facies (?inner shelf) has laterally discontinuous beds with erosional bases, some of which are hummocky; tops of beds are erosional, HCS may have steep dips, amalgamation of beds is uncommon and there are associated wave ripples. The distal facies (100 km + distant) has beds with only slightly erosional bases, low angle HCS, non-erosional tops, mudstone partings between some beds, but common amalgamation, and rare wave ripples. The HCS, both proximally and distally can be scour and drape or accretionary, the latter generally being associated with smaller-scale structures. Some small-scale (< 5 cm) structures with apparent form discordant "wave" lamination have been found to be hummocky in form or related to polygonal (?interference) ripples. Important inferences from the above data are: 1. erosional bases to HCS beds may be of wave origin; 2. polygonal ripples and small-scale HCS suggest multidirectional oscillatory currents; 3. powerful currents carried sand more than 150 km from the nearest shoreline. Waves were capable of reworking the sand throughout the whole area, though the different intensity of waves determined the particular facies; and 4. amalgamation of sandstone beds can be proximal or distal and is a product, both of frequency of storm waves and the amount of mud available to mantle structures.

INTERPRETATION OF PALEOENERGY LEVELS FROM SEDIMENT DEPOSITED ON ANCIENT WAVE-DOMINATED SHELVES

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Interpretation of energy level is an important part of the paleoenvironmental reconstruction of an ancient wave-dominated shelf, and it has a bearing on the potential for and distribution of reservoir rock and the paleoclimatology, paleooceanography and size of the depositional basin. Traditional approaches to interpreting energy levels include analysis of texture, sedimentary structures, the degree of bioturbation and the thickness of specific depositional facies in a progradational sequence. Numerous problems exist, however. The oceanographic definition of wave energy is inconsistent with most geological usage, and a quantitative distinction between high and low energy levels in the geological sense does not exist at present. Nonetheless, the concept of high and low levels on wave-dominated shelves is a useful geological distinction, although it is not always clear whether the concept applies to ambient energy conditions, those induced by infrequent highly energetic events, or some combination of the two.

The reconstruction of ancient energy conditions is further complicated by the ambiguity of most of the available evidence. The texture of a shelf sediment reflects not only the energy level but also the nature of the available material. Sedimentary structures (cross-bedding, planar lamination, hummocky cross-stratification) depend partly on substrate texture and water depth. The degree of bioturbation is partly a function of substrate character, depth, faunal community and rate of sedimentation. The thickness of facies in a progradational sequence depends on the combined rates of sea level change and sedimentation, as well as on the distribution of erosion forces. Ancient energy levels *can* be assessed, but only after consideration of water depth, nature of available sediment, rate of sedimentation, faunal community and sea level change.

PROGRADATIONAL SUCCESSION OF SHELF SANDSTONES: EXAMPLES FROM THE MAESTRICHTIAN OF MONTANA

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The Bearpaw Shale, Fox Hills Sandstone, Lance Formation, and equivalent strata record the last major regression of the western margin of the Cretaceous interior seaway from the craton of North America. In Montana and Wyoming, the Bearpaw (= Pierre) Shale and Fox Hills Sandstone have a gradational boundary over a thick interval of highly bioturbated claystone, siltstone, and fine-grained sandstone. This gradation records a transition from an outer shelf to a foreshore environment. A distinctive succession of sandstone units punctuates this transition and shows a systematic increase in both thickness and complexity of internal stratification. The lower 10 to 20% of this interval contains thin (0.3 to 1 m), laterally-continuous, fine-grained sheet sandstone bodies characterized by erosional bases, internal horizontal bedding, and topped by ripple-drift cross-laminae. The lateral continuity, lack of bioturbation, and stratigraphic position within surrounding lithotypes suggest deposition during episodic storm-surge conditions on the outer shelf. The middle 20 to 30% of the Bearpaw-Fox Hills transition contains sheet- to lenticular-shaped sandstone units characterized by erosional bases, horizontal bedding, and by the dominance of hummocky cross-stratification. These units record deposition under combined-flow, storm-generated current conditions within the inner shelf. The upper 50 to 60% of the transition is a coarsening-upward succession characterized by large-scale sand bodies with a distinctive ridge-and-swale depositional topography. Ridge crests strike NNW-SSE, and are approximately contour parallel to presumed paleoisobaths of the Maestrichtian shelf. Internally, these sandstone bodies have erosional bases, low-angle inclined bedding, hummocky cross-stratified intervals, and trough cross-stratified channel scours near the crests. Ridges are overlain by marine strata and evidence of subaerial exposure

has not been found. The ridge system was apparently nucleated during storm-surge conditions, and later modified by contour-parallel currents. The entire transitional interval is overlain by foreshore, strand plain, and continental sediment, marking the final withdrawal of the seaway from the western craton of North America.

ORIGIN OF HUMMOCKY CROSS-STRATIFICATION: PART 2. PALEOHYDRAULIC ANALYSIS INDICATES FORMATION BY ORBITAL RIPPLES WITHIN THE WAVE-FORMED FLAT-BED FIELD

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Numerous studies of hummocky cross-stratification (HCS) suggest an origin due to storm-generated surface gravity waves. On the shelf, storm waves generate various combinations of unidirectional, oscillatory, or multidirectional flow components; the relative importance of these in the formation of HCS is unknown. In part 1 of this talk (Leckie and Duke), geological evidence is presented indicating that many ancient examples of HCS, which occurred in very fine to fine sandstone, formed under identical hydrodynamic conditions to straight-crested symmetrical gravel dunes. We can precisely determine generative conditions for the gravel dunes, and thus also for the HCS. The gravel dunes are traditional orbital ripples formed under oscillatory-dominant flow; their spacing (λ_G) is related to bottom orbital diameter (d_o) by $\lambda_G \simeq 0.65\ d_o$. Knowing grain size, grain density, and fluid density, we can determine the ratio of maximum orbital speed (U_m) to period (T) from empirical studies. On a graph of U_m vs. T, isograds of d_o and U_m/T have opposite slopes; using this nomogram, the intersection of the appropriate isograds will alone determine generative values of U_m and T for the gravel dunes *without* making prior assumptions about wave parameters or water depth. This method has been successfully tested with recent occurrences for which depth and wave parameters are known. For the ancient gravel dunes, U_m = 0.8 to 1.3 m/s and T = 5.3 to 6.4 s. These calculations are for incipient motion; actual U_m values may have been slightly larger, with slightly smaller T values. These conditions fall within the wave-formed flat-bed field for very fine to fine sand. Form wavelength of HCS (λ_H) associated with these gravel dunes was measured; the ratio $\lambda_G/\lambda_H \simeq 0.65$; thus, $\lambda_H \simeq d_o$. These conclusions are consistent with an independent paleohydraulic analysis of HCS from an ancient lake (Duke, 1984). Thus, independent lines of evidence indicate that HCS is formed under oscillatory-dominant flow within the flat-bed field by low-amplitude, three-dimensional orbital ripples possessing a characteristic spacing approximately equal to d_o.

LARGE STORM-AND CURRENT-SHAPED SAND BODIES ON THE SOUTHEASTERN AUSTRALIAN SHELF

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The coast of southeastern Australia has a high-energy embayed and cliffed coast that receives only minor amounts of modern sediment from streams. This setting, coupled with an apparently stable sea level for the past 6000 years, results in a thin erosional veneer of Holocene sediment overlying truncated Pleistocene and older deposits on the shelf. In several locations, however, large sand bodies have accreted on the lower shoreface and these sand bodies are unlike those described from other shelves in the world. They are 10 to 30 m thick, several kilometres wide, tens of kilometres long, and result in a convex shoreface profile. Radiocarbon dates indicate that most of the sand bodies were deposited in the past 6000 years after the sea level reached its present position. From the study of the texture and composition of long-core samples, it appears that the sand was derived from adjacent beaches and cliffs, and seismic-reflection profiles indicate progradation of sand bodies has occurred across the steep (2° to 5°) seaward flank into water depths of 60 to 80 m.
Three major factors appear to control formation of these sand bodies: an initially steep inner-shelf profile; local high-energy conditions; and a long time period of a stable sea level. Based on sediment texture, seaward dipping reflectors, and surface channels, we infer that sediment is transported seaward from the upper shoreface to the sand bodies by storm-induced downwelling. In areas of strong regional flows, such as off Cape Byron, where the East Australian current impinges on the coast, these flows play a major role in modifying the shape and textural character of the sand bodies.

EXPERIMENTAL EVALUATION OF GENERALIZED SUSPENDED SEDIMENT TRANSPORT THEORY

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Accurate, physically-based sediment transport and flow theories that are applicable under a wide range of conditions are important to marine geological problems, both modern and ancient. Interpretation of ancient environments and predictions for modern, difficult to measure processes, such as continental shelf storms or turbidity currents, rely heavily on generalized theories. To accommodate this need for a more generalized suspended sediment transport theory, higher-order effects, such as multicomponent sediment distribution, sediment-induced density stratification, and near-bottom flow field interaction have recently been added to existing theories. In order to evaluate the usefulness of these and other complicating additions under controlled conditions, the present generalized gravitational theory of Smith and McLean (1977) was tested against the laboratory flume experiments of Vanoni (1946), and Einstein and Chien (1955). Combining data from these experiments allows the theory to be tested against a wide range of sediment and flow parameters. Settling velocities range from 1.18 to 17.25 cm/s, nondimensional volume concentrations from 2.5×10^{-7} to 2.3×10^{-1}, and shear velocities from 2.5 to 18 cm/s. Results of comparisons between the theory and experiments show that the theory works well under a wide range of sediment and flow conditions in predicting vertical-velocity and suspended-sediment profiles. Under sediment transporting conditions, the eddy diffusion coefficient is modified by a Richardson-number-based stratification correction to account for the sediment-induced stable density stratification. The correction is calculated from the local vertical concentration gradient, thus permitting von Karman's constant to retain its clearwater value of 0.40. Also under transporting conditions, the roughness parameter Z_o is increased substantially over the nontransporting Nikuradse Z_o because of the extra momentum extracted from the flow by the transporting sediment. As sediment concentrations increase to large values, the bulk density and viscosity are systematically increased, causing settling velocities to decrease.

STORM GENERATED SANDSTONES AND THEIR DEPOSITIONAL GEOMETRY IN A MIOCENE RESERVOIR FROM THE NORTH COAST OF BORNEO

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The reservoir interval studied forms a small part (20 to 25 m) of a thick succession of nearshore and deltaic sediments that filled the Baram delta basin in northwest Borneo from early Miocene to Recent times. Cores recovered from the interval contain silty to sandy shale punctuated by sandstone units, which occur as either relatively thin (0.3 m), sharp-based, single, fining-upward units or as thicker amalgamations (0.3 to 2 m) of several, erosive-based, incomplete, fining-upward sequences. Available paleontological data, and the internal facies of the sandstones (parallel to low-angle laminae interpreted as hummocky/swaley cross-stratification), imply deposition in a wave-dominated shelf environment where the coarser sands were derived from the shoreface during storm events.
The vertical distribution of facies throughout the reservoir interval, in particular the upward increase in 1. sand percentage and sand bed thickness; 2. the preferential preservation of physical, as opposed to biological, sedimentary structures; and 3. the tendency for sand amalgamation, are consistent with either regression and shoaling of the shelf or up-building of submarine bars. On account of close well control in the study area, individual sands and composite bed packages could be correlated and mapped. The resulting maps indicate that individual storm sands are laterally discontinuous and, where amalgamated, have the form of offshore bars that are approximately parallel to the coast.
Storm deposits have been increasingly recognized in recent years, but there is a

lack of data on their three-dimensional geometry and architecture. This study indicates that a knowledge of that data is essential to the understanding of the depositional processes involved, as storm deposition may frequently be followed by extensive reworking by other shelf processes.

HUMMOCKY CROSS-STRATIFICATION: SHELF OR SURF?

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Primary sedimentary structures exhibiting the three diagnostic criteria for single sets of hummocky cross-stratification (Harms *et al.,* 1982) have been found in the surf zone of a storm-wave dominated coastline in the Canadian Great Lakes. Epoxy peels of box cores (0.45 × 0.30 m) reveal hummocky lamination in well sorted, fine sands in water depths less than 2 m, under conditions of wave breaking and strong longshore currents. The scales of the hummocks with wave lengths of 0.3 to 0.6 m are somewhat smaller than the classic ancient analogues, but the ratio of length to height ranges from 8 to 12 and overlaps the range for hummocky cross-stratification. Depth-of-activity rods have been used to identify those hummocks formed during sediment transport events when the near-bed currents were recorded directly using electromagnetic flowmeters. The results of such experiments clearly show that hummocky lamination was produced by an actively growing bed form with little or no lateral migration. The hummocks occur under conditions close to those expected for a flat bed. In one vertical sequence, the hummocky cross-lamination is underlain by subhorizontal, planar lamination and overlain by undulatory lamination, which grades upwards into small-scale, trough cross-lamination. This sequence was associated with a single storm and appears to represent a combined-flow regime sequence with the hummocky lamination representing a post-vortex (?) ripple bed form. At the time of hummocky formation, near-bed oscillatory flows were dominant and reached 1.4 m/s with a superimposed longshore current of 0.27 m/s. However, the latter was decreasing rapidly and may well have been the cause of vertical growth of the hummock. Hummocky cross-stratification is, therefore, a primary sedimentary structure that can be formed by combined oscillatory and superimposed unidirectional flows, in very shallow surf zones.

FACIES ASSOCIATIONS IN STORM- AND CURRENT-INFLUENCED SHELF SETTINGS, LOWER CRETACEOUS VIKING FORMATION, SOUTH-CENTRAL ALBERTA

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Regional studies, involving 185 cores and over 300 well logs, show that deposits in the Caroline-Garrington-Harmattan fields are typical of the Viking Formation. Three main depositional events occurred: 1. construction and progradation of a clastic wedge associated with a shoreline; 2. cut-and-fill of channels that dissect the clastic wedge in the offshore shelf; and 3. deposition of sheet-like sandstones and conglomerates in the offshore shelf. Some of these sheets have been reworked into 5 to 10 m thick ridge-and-swale deposits. The Caroline-Garrington fields are characterized by a 20 to 35 m thick coarsening-upward sequence of shale, sandstone and conglomerate/pebbly sandstone. Three facies associations comprise the composite sequence: 1. interbedded, bioturbated and loaded fine-grained sandstone and shale (20 to 25 m thick); 2. fine-grained sandstone (6 to 12 m thick) with low-angle inclined cross-stratification; and 3. chert-pebble conglomerate and pebbly to coarse-grained sandstone (0 to 4 m thick). All of the facies thin and become finer grained to the north-northeast, corresponding to an increasing paleowater depth and more distal setting. At Caroline, progradation of the clastic wedge controlled the facies distribution. At Garrington, marine reworking of the sediment was more important. Locally, conglomerate and coarse-grained sandstone occur as lag deposits on ridge crests and in swale troughs. Ridge-and-swale paleotopographies predominate in proximal shelf areas; more sheet-like deposits characterize distal shelf settings. The Garrington deposits are distal equivalents of the clastic wedge at Caroline. In particular, thin "grit" units located above the main Viking deposits at Garrington can be correlated with coarser grained units at Caroline. These "grit" units can constitute a distinct petroleum reservoir. At Harmattan, the location of the best reservoir rocks is controlled by quite different sedimentological features. Here, the major paleotopographic feature is an east-west oriented channel (15 km long × 1.8 km wide × 2 m deep), which cuts through the clastic wedge deposits. The fill consists of chert-pebble conglomerate that occurs as three fining-upward sequences. Maximum net pay is along the trough.

EVENT DEPOSITS IN THE BUDE FORMATION (UPPER CARBONIFEROUS, SOUTHWEST ENGLAND) — TURBIDITES, TEMPESTITES, OR BOTH?

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The Bude Formation consists of at least 1 km of interbedded mudstone, siltstone and very fine sandstone, showing no obvious cyclicity, deposited in a foreland-basin epeiric sea that embraced much of southwest England. Many of the sandstones are thin (< 30 cm), with sharp bases, grading, and other features indicative of deposition during a single, waning-energy event. Other sandstones are composite units, up to 10 m thick, consisting of amalgamated event deposits. Marine fossils are very scarce, suggesting poor oceanic connections. From the abundance of graded beds showing the vertical sequence "sharp base ± massive texture ± parallel lamination ± asymmetrical ripple cross-lamination", and the lack of evidence for wave activity or subaerial exposure, several workers have concluded that the sandstones were deposited as turbidites beneath storm-wave base. However, recent field observations by the author cast doubt, firstly, upon the authenticity of many of the supposed turbidites, and, secondly, upon the validity of the deep-water model, by revealing that most of the ripple cross-lamination in the Bude Formation is of an asymmetrical, wave-influenced variety. Furthermore, mud-filled scours and hummocky cross-stratification, typical of wave-dominated offshore successions, seem to be common.

It is suggested, therefore, that deposition took place largely *above* storm-wave base. Those event deposits containing hummocky cross-stratification and/or wave-influenced ripple cross-lamination are interpreted as tempestites, deposited during storms under the joint influence of sediment-supplying unidirectional currents and wave-induced oscillatory flow. Event deposits showing only massive texture and/or parallel lamination could be either tempestites *or* turbidites, since both of these sedimentary structures can form under unidirectional, oscillatory, and (presumably) combined flows.

A MODEL OF SEDIMENT EROSION, DEPOSITION AND DISPERSAL ON A CONTINENTAL SHELF

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A recent theoretical model of sediment erosion, transport, and deposition caused by the interacting waves and currents on a continental shelf is used to predict changes in the size distribution of a heterogeneous sediment bed and the formation of micro-stratigraphy during storms. This one-dimensional, vertical model includes the feedback interactions between the structure of the benthic boundary layers, resuspended sediments, density stratification, and the composition of the bed. The oceanographic processes are linked to their geological effects via an armouring model that provides for selective removal of finer sediment and for the movement of coarser material as migrating ripples. The passage of a modeled storm event over the mid-shelf sediments results in the formation of graded strata of the order of 0.5 to 5.0 cm thick, composed of the reworked sands and the successively finer sediments redeposited from suspension. When applied at an array of locations on the Washington continental shelf, the model allows assessment of the relative impact of waves and currents during both frequent and extreme sediment-transporting events. Results from well-posed models such as this provide a new tool for interpreting the patterns of erosion, deposition, and dispersal of sediments in shelf environments.

BED FORMS AND SAND TRANSPORT PATHS IN NON-TIDAL CURRENTS, NORTHWEST EUROPEAN SHELF

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A permanent contour current, which moves sand northward along the upper 550 m of the slope west of Scotland, forms sand waves up to 2 m high. This current may occasionally sweep across the outer shelf and into the North Sea. Preliminary results from a numerical model have been used by R. Flather to investigate the distribution of extreme currents associated with tides and surges. The maximum computed surge currents from 16 storms exceed 60 cm/s on much of the outer shelf in depths of 100 to 150 m and exceed 100 cm/s in some parts of the North Sea. Tidal, surge and wave oscillatory currents are strong enough, particularly when combined, to move sand on most parts of the shelf.

An attempt is made to determine areas dominated by tides, waves and surges in Northwest European seas, whilst accepting that much of the shelf will be affected by considerable variation in flow conditions. Most of the larger bed forms found in tide-dominated areas (R. Belderson, this meeting) can be found in surge-dominated areas. However, large, sharp-crested, symmetrical sand waves are exclusive to tidal areas.

Tabular sand patches are found only on those parts of the open shelf where the modelled values of extreme surge current and tidal current are less than the threshold velocity for sand transport. They are usually symmetrical, with relatively steep edges (up to 15°), very broad flat tops and a height of 2 to 3 m. They consist mainly of fine sand, but some of them are known to be intermittently buried by mud. Bioturbation is common. These neglected bed forms have been described from a number of wave-dominated shelves. As they are one of the few bed forms from Holocene shelves that appear to be indicative of wave dominance, it is important to discover their internal structure. Apart from a low sand supply, they have many of the characteristics of environments where hummocky cross-stratification has been predicted.

CARDIUM FORMATION LITHOFACIES DISTRIBUTION IN THE PEMBINA OILFIELD AREA, WEST-CENTRAL ALBERTA

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Deposits of the Cardium Formation at Pembina are characterized by an upward-coarsening interval, commencing at the base with black, bioturbated shale and shaly siltstone that incorporates increasing amounts of very fine and fine sand. Bioturbation also characterizes this interval, although it drops off very quickly toward the top, where distinctly bedded sandstones and shales dominate. Chert conglomerates cap the sequence.

The thickness and distribution of lithofacies that comprise this upward-coarsening interval are extremely variable across the field. Rapid vertical variability is a common characteristic in core samples. Correlations of closely spaced cores indicate clearly that lithofacies are also characterized by a rapid lateral change. Complex patterns of sedimentation and scour define the upper high-energy part of the sequence. This arrangement is controlled by input of sediment into the area, scour of pre-existing deposits, and subsequent resedimentation. The results of these processes can be observed in outcrops where, in addition to hummocky cross-stratification, large scours, rib and furrow structures, and boulder conglomerates of surrounding lithologies are evident.

Field wide maps of the top surface of the reservoir display a ridge-and-swale topography formed by accumulations of conglomerate and scouring processes, respectively. Ridges measure approximately 13 to 18 km in length and 3 to 8 km in width. The contact between the conglomerate and underlying sandstone is similarly controlled by scour. This surface exhibits a subdued ridge-and-swale topography. Ridges on this surface measure approximately 9 to 17 km in length and 2 to 6 km in width.

SEDIMENTOLOGY OF A TEMPESTITE: EPISODIC DEPOSITION IN THE CARDIUM FORMATION, PEMBINA OILFIELD AREA, WEST-CENTRAL ALBERTA

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Deposits of the Cardium Formation in the Pembina oilfield area comprise five lithofacies: 1. bioturbated, dark grey shale; 2. bioturbated, thin- to very thin-bedded, fine-grained shale, siltstone and fine-grained sandstone; 3. thin- to very thin-bedded, fine-grained sandstone, siltstone and black shale; 4. medium-to thick-bedded, very fine- to fine-grained sandstone; and 5. conglomerate. All five lithofacies reflect a marine depositional environment, corroborated by the characteristic sublittoral to bathyal trace fossil fauna. Deposits of lithofacies 5 and the underlying lithofacies 4 are not contemporaneous, although they accumulated in a similar environment. The conglomerate is in contact with all the other lithofacies and incorporates shale, siderite and sandstone clasts. In contrast, chert granules and pebbles, characteristic of lithofacies 5, are extremely rare in the underlying lithofacies, except near the contact with lithofacies 4, where mixing through bioturbation has occurred.

The sedimentary sequence is characterized by a transitional interval from bioturbated beds with decreasing shale content upward to sandstone deposits with parallel lamination as follows: low-angle inclined stratification; flaser, lenticular and wavy bedding; scour and fill structure; load casting; graded bedding; in-phase, climbing, convex and truncated-crest ripples; lithoclasts of surrounding lithologies; and destruction and truncation by scour of bioturbation traces, in sandstones and conglomerates. Capping conglomerates are, generally, poorly sorted and commonly contain shale as drapes and interbeds. Evidence for physical and biological reworking of these deposits is abundant and is distributed discretely, suggesting that contrasting energy regimes affected the overlying water column. Biological reworking of these rocks would have occurred during periods of low water agitation and turbulence. Conversely, recurring and frequent physical reworking would have taken place during periods of high agitation and turbulence. These contrasting responses are the product of sedimentation below fair-weather wave-base and above storm-weather wave-base.

ORIGIN OF HUMMOCKY CROSS-STRATIFICATION: PART I. STRAIGHT-CRESTED, SYMMETRICAL GRAVEL DUNES: THE COARSE-GRAINED EQUIVALENT OF HCS

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Hummocky cross-stratification (HCS) and symmetrical gravel dunes (large-scale, coarse-grained, oscillatory wave ripples) commonly occur in close juxtaposition to one another in ancient sediments. If sediment is medium- to very coarse-grained, pebbly sandstone, then two-dimensional, symmetrical gravel dunes will be formed by bidirectional, oscillatory flow; if sediment is very fine- to fine-grained, then three-dimensional HCS will be formed by hydrodynamically similar currents. There is increasingly more documentation of symmetrical gravel dunes from modern shelves, whereas modern examples of hummocky cross-stratification are uncommon. Characteristics of two-dimensional gravel dunes can provide an insight to the nature of waves responsible for generating three-dimensional HCS. Ancient symmetrical gravel dunes are two-dimensional, with crest to trough heights of 10 to 15 cm and wavelengths of 70 to 130 cm. Crest shapes are rounded, although slightly peaked or flattened crests also occur. Crests are generally rectilinear, but can be slightly sinuous or have an anastomosed pattern. Coarser material is concentrated in troughs with more fine material near the crests. Crest orientation approximates paleoshoreline trends. Dip directions (a-b plane) of pebbles on opposing sides of dune crests dip in opposing directions, perpendicular to crest orientation. There is limited evidence from dune stratification that some symmetrical dunes may have been migratory. The conglomerate on which ancient symmetrical gravel dunes formed commonly has a sharp base, and is occasionally graded with solemarks, implying a sudden introduction of sediment, probably as a density current. This association is analogous to that of HCS. Modern symmetrical gravel dunes are formed on relict Pleistocene sediments in water depths of 5 to 100 m, formed by storm waves and onshore propagated swell. Symmetrical gravel dunes are orbital wave ripples, formed by bidirectional oscillatory flow. Wavelength of gravel dunes approximates orbital diameters of the waves ($\lambda = 0.65\ d_O$). Characteristics of flows that formed gravel dunes can be applied to the formation of HCS. Flow conditions that are capable of moving pebbles on symmetrical gravel dunes would generate the upper flat bed conditions of HCS.

CONTROLLING FACTORS AND IMPORTANT DIFFERENCES OF SEDIMENTARY PROCESSES AND PATTERNS IN UNIDIRECTIONAL-CURRENT-DOMINATED EPICONTINENTAL (EPEIRIC) SHELVES

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The northeastern Bering epicontinental shelf is a large (200 by 500 km) shallow (<50 m) epeiric seaway that is surrounded by a peripheral coastline; it is characterized by a major sediment source (the Yukon River) and a permanent northward geostrophic current. The strong, unidirectional flow, reinforced by episodic storm-associated currents, controls: 1. the distribution of sediment facies that may or may not be parallel to shorelines; 2. the distribution of biofacies that are related to current-controlled substrate gradations, not to shoreline proximity; 3. the formation of lee-side sand bodies extending as far as 100 km behind islands and westward-projecting land masses; 4. major sediment advection from the Yukon River to depocentres 100 to 1000 km northward;

5. the progradation of storm-sand layers more than 100 km northward from the Yukon delta; and 6. the formation of major unidirectional sand-wave and scour-depression fields on the east sides of straits. This environment is also subject to synergistic combinations of gas-charged sediment, storm-wave loading with sediment liquefaction, and unidirectional ebbflow from storm surge that results in significant sediment resuspension and transport to depocentres far from sources.
Thus, the interpretation of sedimentary processes, and patterns, and paleogeographic reconstructions in epeiric seaways, cannot be based on depositional models of marginal shelves where sedimentation is associated with diminishing energy seaward from waves and storm-driven currents. Biofacies and lithofacies gradations in epeiric seaways dominated by unidirectional currents are controlled by topographic setting and current shear, not by distance from shoreline or depth. Depocentres may be laterally extensive, thin, and displaced far from river sources. Large linear sand bodies with innershelf biofacies and lithofacies may form oblique to, and tens to hundreds of kilometres from, the coastline or sediment sources.

EVIDENCE OF WAVE-DOMINATED, SELECTIVE TRANSPORT AND DEPOSITION OF HEAVY MINERALS IN UPLIFTED PLEISTOCENE SHELF SANDS ALONG THE OREGON COAST

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Sedimentologists commonly rely on selected mineral phases in shelf sediments to establish sediment sources and transport patterns. Unfortunately, selective sorting processes in the wave-dominated nearshore can strongly bias mineral composition of shelf sands, leading to misinterpretation of mineral assemblage analyses. However, if regional variation in sediment grain size and grain density is properly interpreted, then sorting processes and associated mechanisms of shelf sediment transport can be established. Such interpretations of nearshore placer deposits have been used by the authors to document wave-dominated northward transport of shelf sediments along the Oregon coast during Holocene and Pleistocene times.
Along the central Oregon coast, exposed placer deposits rich in ilmenite (density 4.7 g/cm^3) and chromite (density 5.2 g/cm^3) have been extensively sampled, together with quartz-rich sands from a series of modern beaches and the Seven Devils terrace, a transgressive Pleistocene shelf sequence. Grain size and grain density relationships between quartz, pyroxene, and the placer oxide minerals in microlaminations demonstrate flow shear mechanisms for the selective enrichment of the dense oxide minerals. On a regional scale (tens of kilometres), enrichment of the fine-grained heavy minerals occurs at the northern end of littoral cells defined by major headlands, for both modern beach deposits and for the Seven Devils shelf sequence. Large winter surf from the south drives strong longshore currents to the north, carrying both light and heavy minerals to the northern sections of modern littoral cells. Swell direction reverses during the summer months and weak southward-trending currents transport only less dense quartz and feldspar grains southward. A similar transport mechanism is envisioned for the enrichment of heavy minerals in the Seven Devils terrace deposits. Interestingly, the extreme enrichment of heavy minerals (>80% by weight) in the lower facies is reflected to a lesser degree throughout most of the shelf section, indicating the importance of the initial selective transport process in determining local shelf sediment composition.

HCS: PROBLEMS, PERSPECTIVES AND MISUNDERSTANDINGS

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Hummocky cross-stratification (HCS) has become generally accepted as a structure reflecting sedimentation of coarse silt to medium sand entrained by storm-wave-induced currents, giving evidence of deposition between storm and fair weather wave bases. Dott and Bourgeois have proposed an idealized HFXM sequence thought to represent a waning flow sequence deposited by storm-waves that is succeeded by fair weather sediments. However, wave-rippled tops are often absent in HCS units from deltaic sequences and the X-zone is frequently composed of unidirectional current ripples. This suggests that oscillatory currents play, at best, a relatively minor role in the genesis of HCS. The absence of wave-rippled tops to HCS in deltaic sequences suggests that river flood processes were responsible for HCS deposition. It is possible that wave ripplied tops to HCS units in shoreface sequences may occur merely because the HCS was deposited there by storm-surge/wind-forced currents. Evidence will be presented showing that "hummocky" bed forms may be subdivided into three lamination types: basal laminae overstepping one another laterally at a very low angle across a flat basal surface (lateral accretionary type); progressive thickening of laminae over hummock crests (pinch-and-swell type); and the mantling of a differentially scoured hummocky surface (scour-and-drape type). Walker and Leckie have proposed the term swaley cross-stratification (SCS) for shallow scours within amalgamated sandstone bodies containing only rare convex-upward surfaces. However, in practice, the distinction between SCS and amalgamated scour-and-drape type HCS is rather arbitrary. Furthermore, SCS conforms to descriptions of wave-produced scours produced during fair-weather periods in the high-energy, non-barred nearshore environment and may possibly be of a similar origin. In contrast, lateral accretionary and pinch-and-swell type HCS imply the existence of a hydrodynamic pressure gradient during deposition and may possibly be of a different origin to scour-and-drape type HCS. In conclusion, it is proposed that SCS is not adopted as a sedimentological term. HCS appears to be a 'bucket-term' for a series of lamination styles, which may be polygenetic in origin and not necessarily related to storm-waves. Thus, the adoption of the Dott and Bourgeois conceptual sequence for HCS units appears to be premature.

VARIABLE FACIES SEQUENCES IN CORES FROM THE LOWER CRETACEOUS VIKING SANDSTONE, SOUTH-CENTRAL ALBERTA

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The Lower Cretaceous Viking Formation in south-central Alberta is an asymmetrical transgressive-progradational cyclic succession within which two major progradational sequences are recognizable. Cores of the Viking Formation depict a range of facies sequences depending upon geographic position within the depositional basin, and upon stratigraphic position within the overall cyclic succession. This variability in facies association is amply illustrated by comparison of cores from the Joffre and Caroline oil fields. Individual core sequences from Joffre exhibit evidence for both wave-dominated and current-influenced shallow shelf settings. The composite sequence is interpreted to reflect shoreface progradation in a wave-dominant setting, followed by transgression and subsequent deposition of coarse-grained detritus by inner shelf currents, seaward of the shoreface toe. The cored sequence at Caroline is part of a younger progradational sequence, and is characterized by a shoreline-attached, prograding shoreface sand wedge, within which the influence of storm-wave deposition was prevalent. The Caroline sandstone is also truncated by conglomeratic sandstone deposits, which are thought to record the onset of another major transgressive event.

A MODEL FOR DEPOSITION SEAWARD OF THE OFFSHORE BAR DUE TO STORMS OF EXTREME INTENSITY

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The stratigraphic record on a continental shelf commonly contains sediment introduced by background deposition, modified by extreme events, and reworked by the activities of benthic organisms. If the mean frequency of extreme events times the mean thickness of the storm-affected layers is large relative to the rate of background deposition, then the storm deposits will be amalgamated. If this product is also large compared to the rate of reworking of these sediments by marine organisms, or if the mean storm deposit thickness is greater than the depth of reworking, then the significant stratigraphic signature will be of the extreme events. The situation where a storm-generated stratigraphy dominates is typical of the dynamic region just seaward of the offshore bar. Early in major storms, sediment is transported toward this bar crest from both sides, causing the bar to grow in height; eventually, however, during the events that leave a stratigraphic signature, the largest waves begin breaking seaward of the bar top. Relatively rapid shoaling on the offshore side causes the largest of these waves to plunge, taking material from the bar face into suspension and creating a field of turbulence that partly supports the suspended sediment. The result is a bulk-fluid-density-induced pressure gradient that overwhelms the mean onshore bottom flow responsible for building the bar in the first place, producing a pulsating density current with a net motion in the offshore direction. The largest waves break at random locations on the offshore side of the bar, resulting in an erosional topography characterized by irregular swales that are quickly draped with material settling out of suspension. Calculations using conditions typical of the northern California to southern Washington shelf indicate that scours several tens of centimetres in depth with spacings of several metres would be draped with a series of layers, each of which ranges from a millimetre to nearly a centimetre in thickness. The predicted stratigraphic record would be similar in style and scale to the hummocky stratification found in Cenozoic and Cretaceous rocks exposed along this coast.

LABORATORY STUDIES OF OSCILLATORY-FLOW BED CONFIGURATIONS AND THEIR BEARING ON STRATIFICATION IN SHALLOW-MARINE SANDS

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Studies using wave tanks, especially those with oscillatory-flow ducts, show that symmetrical oscillatory flows produce several kinds of bed configuration as a function of sediment size, oscillation period, T, and maximum orbital speed, U_m (or orbital diameter). Differences in flow in these two kinds of apparatus do not seem to result in fundamental differences in bed configuration. At small to moderate T (8 to 10 s) in very fine to fine sands, vortex ripples are the stable configuration. These are known from meager but clear laboratory data to be strongly three-dimensional in the upper range of U_m, especially at large T. Systematic field observations on three-dimensional vortex ripples are lacking. The bed geometry is that of hummocks and swales with moderate to negligible anisotropy in plan view, and three-dimensional ripples become less steep and more rounded with increasing U_m. The upper limits of U_m, T, sediment size, and ripple spacing for three-dimensional vortex ripples is not yet known experimentally, but maximum ripple spacing is at least 1 m (when scaled for cold water). The possibility that the transition from two- to three-dimensional vortex ripples is a consequence of the small size of oscillatory-flow ducts or the presence of side walls seems unlikely, because in the same experimental arrangement, vortex ripples in coarse sands remain two-dimensional for the highest U_m and T studied so far. The scarcity of hummocky cross-stratification in sands coarser than 0.25 mm, together with the lack of large-scale ripples in sands finer than about 0.2 mm in dominantly unidirectional flows, suggests that most of such stratification is produced by three-dimensional vortex ripples during deposition from suspension. This interpretation is clouded by the absence of experiments on deposition and the uncertainty about the upper range of conditions for the existence of three-dimensional vortex ripples. Hummocky cross-stratification is likely to be polygenetic in any case; some stratification styles that would be described by that term are probably produced by combinations of oscillatory and unidirectional flow. Experiments on bed configurations in combined flows, especially at high flow velocities and under depositional conditions, are badly needed as a guide to what might be encountered in natural flows.

COMPARISON OF SAND RIDGES ON THE NEW JERSEY CONTINENTAL SHELF, U.S.A.

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Two linear sand ridges from the nearshore and middle parts of the New Jersey continental shelf were sampled using vibracores and box cores. Lithological descriptions were made of the cores, based on epoxy peels, X-ray radiographs, and impregnated core slabs and grain size analysis. Vibracores obtained for the study have an average penetration of 6 m and 95% recovery. Box core samples revealed lithologies and relative abundance of physical and biogenic structures found in the upper 25 to 46 cm of the sediment. Bottom topography was established on the basis of 3.5 kHz seismic data.

The nearshore sand ridge that was sampled (74°22'W, 39°19'N) exceeds 5 km in length and ranges up to 2 km in width and has a relief of 6 to 10 m. The mid-shelf ridge (74°08'W, 39°09'N) is nearly 4 km long, up to 1 km wide, and has a relief of 10 to 11 m.

Three to four general lithological units were recognized; these may be common to both ridges. At the base of many of the cores, nonskeletal mud and poorly sorted sands are present; some of the interlayered sands and muds contain laminations and abundant pebbles. Overlying this unit in the nearshore ridge is a shell-rich mud and sand interval that is relatively massive (bioturbated). This lithology was also recovered in one core from the middle shelf ridge. C-14 dates taken from the shell-rich units indicate that the middle and nearshore ridges differ in age by more than 6000 years.

The top unit in all the cores is a fine- to medium-grained sand, here termed the upper ridge sand. This unit is similar in both ridges and consists of laminated, stacked beds ranging from 3 to 71 cm in thickness, and generally coarsens upward. This unit in the near shore ridge system has a slightly coarser mean grain-size range (150 to 400μ) than the mid-shelf ridge (130 to 350μ). Both ridges contain alternating laminated- and non-laminated bed sequences.

LINKS BETWEEN SUSPENDED AND BED LOAD SAND TRANSPORT RATES ON THE LONG ISLAND INNER SHELF, NEW YORK, U.S.A.

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Measurements of suspended sand profiles using a 3 MHz pulsed acoustic concentration meter (ACM) and calculations of the quantity of bed load that is *mobile under combined waves and steady currents, indicate that bed load* transport and suspended-sand concentrations are linked through the bed load concentration. The instantaneous bed load transport $\vec{q}_v(t)$ during each burst, was estimated using the method outlined in Grant and Madsen (1979) to obtain the Shields' Number $\psi(t)$ for a combined wave current $\vec{U}_w(t)$ and steady current $\vec{U}_a$, and the empirical equation of Vincent *et al.* (1981), $\vec{q}_v(t) = (0.09 \pm 0.03)\ (\psi(t) - \psi_{TH})\vec{U}(t)$, where ψ_{TH} is the critical Shields' Number *for the bed sediment and* $\vec{U}(t)$ *is the instantaneous current* vector $(\vec{U}_w(t) + \vec{U}_a)$. This equation can be rewritten as: $\vec{q}_V(t) = c*(t)\vec{U}(t)$, where $c*(t)$ is the volume of material that is mobile per unit area of the bed. The average bed load transport rate $\vec{q}_V$ can be found by integrating over a period that is large compared with the wave period. The transport direction will generally not be the same as that of the steady current (Vincent *et al.*, 1983). The ACM profiles over a single burst show that there is a great variation in sand concentrations in the bottom few decametres of the flow, and that concentrations are coherent with the peaks of the wave packets rather than with the passage of individual waves (Clarke *et al.*, 1982). Suspended sand concentration C_z profiles, temporally averaged over a burst (256 s) and then spacially averaged into 10 cm vertical sections, were found to fit closely to a log-linear profile, $C_z = C_1 (1 - A \log_e{}^{z/z_1})$, where C_1 is the concentration at height z_1 (= 1 cm) and A was empirically determined as 0.22±0.005 (Vincent *et al.*, 1982). A linear correlation was found between $c*$ and the suspended- sand concentration at 1 cm above the bed, C_1. The correlation coefficient was 0.82 (significant at 1%).

WAVE AND CURRENT PROCESSES ON A WAVE-DOMINATED SHELF

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Waves and currents are two factors that influence the movement of sediments on many shelves, but their relative importance changes with depth and shelf topography. Waves contribute to both the resuspension of finer sediment and to the bed load transport of coarser material, and result in the following processes: 1. shoreward bed load transport of material due to wave asymmetry (important in water <10 m deep); 2. wave resuspension of the coarse material for short periods (<wave period) and of finer material for considerably longer (>>wave period); and 3. wave pumping of fine sediment into suspension due to the pressure gradient beneath the crest and trough of the waves. Currents, tidal or storm-driven, are the major determinants of the direction of both bed load and suspended sediment, but for storm-dominated shelves they seldom initiate the transport. The tidal currents can produce an effective diffusive mechanism for sediment dispersal. Wind-driven currents result from the applied surface wind stress and may involve significant coastal upwelling and downwelling due to Ekman transport. Trapped continental shelf waves can also contribute to the currents on the shelf. The interaction between the waves and the currents has two effects: 1. the boundary layer initiated by the oscillatory wave currents changes the bed roughness 'seen' by the steady current and alters the direction of the steady current close to the bed; and 2. bed load transport occurs in a direction determined by the instantaneous wave current plus steady current.

Transport patterns of sediment of different sizes may be quite different, depending on whether the dominant processes result in mainly bed load or suspended load transport. These processes are controlled by the long term climatology of the shelf system, which itself ultimately depends on the frequency and intensity of storms in the region. In deeper water out toward the shelf break, the transport events will become more episodic and increasingly dependent on the few very intensive storms. The statistics of the storms are, however, not well documented and their effects on the sediments are, as yet, unmeasured.

WAVE-DOMINATED SHELVES — A GEOLOGICAL POINT OF VIEW

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The geologist identifies two main problems of wave-(storm) dominated shelf deposition — what are the characteristic associations of sedimentary structures (i.e., facies), and how was the sand emplaced in the first place? The structure which has received the most attention recently is hummocky cross-stratification (HCS), and there is now fair agreement that it is formed by storm waves, possibly in combination with unidirectional flows. To preserve abundant HCS requires deposition below fair weather wave base. In one of the commonest HCS facies, namely alternations of bioturbated mudstone with sharp-based HCS sandstone 5 to 100 cm thick, angle-of-repose, medium-scale, cross-bedding is exceedingly rare to absent. Counts of the number of sharp-based sandstones within sections whose absolute ages can be estimated, suggest sandstone recurrence intervals of between 400 to 15 000 years (average of 5 studies is about 5000 years). The geologist therefore recognizes the possibility that these HCS sandstones represent events that marine geologists and oceanographers may never have observed or measured. At least three studies (Fernie-Kootenay transition, Cardium at Ricimus, Wapiabi-Chungo transition) have demonstrated the intimate association of sharp-based HCS sandstones with classical turbidites, with evidence that emplacing flows for both of these facies used the same paleoslope. The implication is that turbidity currents may have been important in emplacing HCS sandstones into the basin, with some paleoflow evidence indicating dispersal down the paleoslope and perpendicular to isobaths. Marine geologists, on the other hand, have emphasized that wind-forced currents and storm-surge ebb currents are deflected by Coriolis forces and mostly flow parallel to isobaths as geostrophic flows. Thus sand is dispersed mostly parallel to the shore, incrementally, over a long period of time. There is little positive evidence in the geological record for incremental geostrophic dispersal of sand, perhaps because the final storm imprint erases evidence for the long term sand transport processes. Clearly, the different points of view both contribute new insights to problems of shelf sand facies and their origin.

Tide-Dominated Shelves

OFFSHORE TIDAL SAND FACIES — BED FORMS AND RELATIONSHIP IN SPACE AND TIME

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Regional investigations of bed forms in relation to peak tidal current strength has allowed the distinction between two major offshore tidal sand facies — the relatively higher energy offshore tidal sandbank facies and the relatively lower energy offshore tidal sand sheet facies. Lack of available sand, however, will lead to the development of a gravel sheet facies in areas where the sandbank facies might otherwise exist. With the exception of the rippled outer margin of the offshore tidal sand sheet and some shallow sandbank crests, both offshore tidal sand facies are generally covered in sand waves. The asymmetry of these sand waves is normally governed by the tidal current maximum bottom stress vector, indicating that although storm-induced currents can exert an influence on their development, the tidal currents play the dominant role. The resulting deposits of both facies (in their active, as opposed to waning phase) are expected to be pervasively cross-stratified (unless the structures are destroyed by burrowing organisms). This could contrast with deposits of other largely storm-generated sand sheet and sand ridge facies. Because the offshore tidal sandbank facies is maintained by relatively stronger tidal currents than the offshore tidal sand sheet facies, it is possible to predict that, where the sandbank facies is identified in ancient deposits, then an associated sand sheet facies should be suspected, both laterally and in the vertical succession. In contrast, where an ancient offshore tidal sand sheet is identified, an association in space and time with the sandbank facies is not a necessary condition. The identification of ancient nearshore and/or tidal flat deposits need not necessarily imply extensive offshore tidal sand deposits, but these should at least be suspected.

EVIDENCE FOR DIURNAL TIDES IN THE UPPER JURASSIC OF THE WESTERN INTERIOR BASIN, U.S.A.

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The Upper Jurassic Sundance Formation in Wyoming has revealed unequivocal evidence for the operation of diurnal tides in the Western Interior Basin in the form of neap/spring bundles of foresets deposited by migrating subtidal sand waves. The upper part of the Sundance Formation comprises a thin, transgressive coquina, a mudstone-siltstone unit with a slight coarsening upward trend (40 m), and a sandstone unit with an erosive base (20 m). The mudstone-siltstone unit is marine, intensely bioturbated and includes in its upper levels numerous thin, discrete beds of wave-ripple laminated sandstone and storm-wave generated coquinas. The sandstone unit with an erosive base exhibits planar and trough cross-bedding, current ripple lamination and flat lamination with parting lineation, and is considered to have been deposited by tidal currents due to: 1. a bimodal, bipolar paleocurrent pattern; and 2. an abundance of reactivation surfaces and millimetre-scale mud drapes in sets of cross-bedding.

Occasionally, cross-bed foresets occur in bundles defined by distinct surfaces with the following sequence: reactivation surface→opposed flow current ripples → mud drape; or lower mud drape→opposed flow current ripples→upper mud drape. The foresets were deposited by the dominant tide, the current ripples by the subordinate tide and the clay drape(s) in stillstand periods between tides, implying extreme time-velocity asymmetry of the tidal currents. Within cross-bed sets the thickness of the foresets bundles varies gradationally between groups of thin (2 to 25 cm) and thick (40 to 110 cm) bundles with a pronounced periodicity of 9 to 14. These systemsatic variations in bundle thickness suggest neap/spring cycles in a diurnal tidal system with sand omission at low neap tides causing the periodicity to be slightly less than 14 on some occasions. These observations confirm the operation of tides in the basin and permit the nature of the tides to be interpreted in detail. In view of the mudstone-siltstone unit being wave-dominated and the sandstone unit with an erosive base being tide-dominated, the succession is interpreted as being a prograding barrier island-tidal inlet system with the mudstone-siltstone unit representing the lower beach face and the sandstone unit the tidal inlet, thus contradicting the offshore bar model of Brenner and Davies (1973, 1974).

FACIES ASSOCIATIONS IN TIDAL/LITTORAL SHELF SETTINGS: LOWER CAMBRIAN GOG GROUP, SOUTHERN CANADIAN ROCKY MOUNTAINS

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In the Kicking Horse Pass area, Gog sediments are mainly interbedded quartzite and shale with rare, thin conglomerate. The dominant facies has trough, planar and tidal bundle cross-bedded (0.3 to 2 m thick) quartzite, with thin (0.5 to 8 cm) shale interbeds. The secondary facies has parallel-stratified quartzite and lensen- or flaser-bedded quartzite and shale. Thick (1 to 3.5 m) lateral accretion deposits occur and sequences are poorly developed. Unimodal paleoflow patterns occur in trough cross-bedded facies toward the base of the section, bimodal paleoflows with planar cross-bedded quartzite occur in the middle of the section, and bimodal-to-random paleoflow patterns occur at the top of the section. This corresponds to an increase in the proportion of massive and parallel-stratified quartzite. The interbedded quartzite and shale at the base and middle of the section have a *Cruziana* ichnofacies, with high diversity and low to moderate density, reflecting the resident ichnocoenosis in a shallow sublittoral setting. The massive quartzite at the top of the section has a *Skolithos* ichnofacies, with a low diversity and high individual density, characteristic of high-energy substrates. The Gog sediments comprise a 110 m thick shoaling-upward sequence from trough and planar cross-bedded quartzite of offshore dune-sandwave complexes, generated by tidal or littoral currents. This is succeeded by high-energy massive and parallel-stratified quartzite with associated *Skolithos* ichnofacies, suggesting a near-shore setting. The offshore sandwave complexes have paleotopography and facies associations similar to the Lower

Cretaceous "ridge-and-swale" deposits recognized in sub-surface reservoirs of Alberta. Significant is the lack of sequence development in the Gog sediments in comparison to these younger Mesozoic sediments.

TIDAL CURRENTS IN CONTINENTAL SHELF SEAS, ANCIENT AND MODERN

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Tides and storms dominate the dynamics of most continental shelf seas. Whereas tides are ever present, storms are intermittent events, generating surface waves and wind-driven/storm-surge currents. The tides are generated in the oceans by forcing at well defined frequencies determined by the Moon's orbit around the Earth and the Earth's orbit around the Sun — predominantly daily and twice-daily, with longer period modulations. The response of a continental shelf sea to the tide propagating into it from the ocean is mainly determined by the shelf's width and depth, largest amplification at the coast occurring for ¼ wavelength (organ pipe) type of resonance. Tidal energy is dissipated in shelf seas by bottom friction and hence the current speed decreases near the sea bed and the sea bed experiences a stress that can sometimes move sand. Since sand transport is generally thought to depend nonlinearly on the current speed, the total current is important, particularly higher tidal harmonics. The principles governing the present distribution of tidal currents in continental shelf seas can be applied to ancient continental shelf seas, based on estimates of the ocean and shelf configurations and the Moon's distance from the Earth.

TIDAL SAND WAVE PROCESSES AND SEDIMENTARY STRUCTURES, PERMIAN, ARIZONA

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The Permian Rancho Rojo Sandstone (0 to 18 m thick), which crops out along 40 km of the southern edge of the Colorado Plateau, central Arizona, was first recognized as a marine sand wave deposit by Blakey (1979). It conformably overlies the fluvial Hermit Formation and grades upward into the marine Bell Rock Member of the Schnebly Hill Formation. We have defined three facies which are interpreted as having been formed in a transgressive estuarine to open marine succession. Facies 1: the basal Rancho Rojo Sandstone comprises giant-scale (3 to 12 m) cross-bed sets interpreted as being estuarine tidal sand wave deposits. Cross-bed foresets dip westward, reflecting sand wave migration related to the dominant tidal current that was probably reinforced by saline density currents. The hypersaline Holbrook Basin (Blakey, 1980) to the east was the likely source of the density currents. Where the giant foresets dip gently ($<17°$), they contain east-dipping, tabular- to wedge-shaped sets of large-scale (5 to 80 cm) cross-beds formed by megaripples that climbed the sand wave lee-slope under the influence of the subordinate tidal current. Where giant foresets dip more than 17°, megaripples were inhibited and sand wave foresets consist of simple, tabular beds, 1 to 25 cm thick. The influence of tidal currents is recorded in these beds by pause planes lined with mud drapes, small mud intraclasts and mud intraclast/mud drape couplets. Facies 2: the overlying facies consists of large-scale (0.1 to 1 m) trough and tabular cross-beds that formed in a shallow marine environment established by continued transgression. Paleocurrents of this facies are strongly biomodal north and south, 90° rotated from the dominant east-west paleocurrents of the underlying facies. A similar relatonship exists today between tidal current directions from onshore (estuarine) and offshore areas in the North Sea. Facies 3: a ripple cross-laminated facies, which indicates further reduction of tidal energy in a deeper marine setting occurs at the top of the succession. This facies association may be generally representative of tide-dominated, transgressive, shallow marine sequences.

THE DYNAMICS AND INTERNAL STRUCTURE OF MODERN INTERTIDAL AND SUBTIDAL BED FORMS

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The results of a research study of bed form movement and internal structure will be presented. Detailed measurements were made on a daily basis over neap/spring tidal cycles. Internal structures were inferred from measurements made by divers at a nearshore subtidal site. These included cross-sectional profiles, recorded at successive slack waters. Sequential profiles were used to determine the positions for box cores at an intertidal site. These were then interpreted in terms of the depositional processes that occurred over known periods of time. In association with these studies, measurements were made of boundary-layer flow, sediment transport, sediment dispersion, and temporal and spatial variation in grain size. Lag cross-correlation techniques were used to quantify form change and bed form migration which, when related to tidal range, give contra-rotating hysteresis loops.

The study of sedimentary structures is fundamental to the geological interpretation of paleoenvironments and the significant sedimentary processes. Despite its importance, insufficient verification of the interpretation of ancient sedimentary sequences has been carried out by studying modern processes. Most of the work that has been undertaken in the marine environment is restricted to the intertidal zone and, despite bed form movement, is limited to single observations. Bed forms with similar sizes to those studied at the nearshore site occur at the shelf edge in water depths of approximately 150 m. Can we distinguish these contrasting environments, including those of the intertidal zone, using traditional stratigraphic criteria?

GEOMETRY AND SEQUENTIAL DEVELOPMENT OF ANCIENT TIDE-DOMINATED SHELF SAND BODIES

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Only a few examples of ancient tide-dominated shelf sand bodies are known in the geological record. One of the reasons for this is that these deposits are rarely preserved. Sand bodies primarily formed by tidal currents generally take the form of a thin veneer on the shelf and are modified either by wave action or by the prograding shoreline system, in the case of a regressive megasequence. The best circumstances for the preservation of tidal sand bodies on the shelf is sedimentation during a progressive rise in sea level or constant basin subsidence. In addition, most of the ancient tidal sand bodies can be found within the inner shelf; the outer shelf usually consists mainly of fine-grained clastics or highly modified sand bodies. An example from the Lower Tertiary Roda Sandstone in Spain shows the change in sand body geometry and the sequential build up from the estuary mouth to the inner shelf. Evidence of tidal action can mostly be found within the estuary mouth and the adjacent ebb tidal delta. Sand bodies on the inner shelf, however, show less evidence of tidal processes. Products derived from modifying processes, such as wave action, are dominant.

The occurrences of tidal sand banks and sand waves on present day tide-dominated shelves have only been supported by a few examples from ancient analogues. After a detailed facies analysis, most of the ancient examples were found to have been formed in more nearshore or even inshore environments. A hypothetical geometrical and sequential model constructed from data of recent offshore sand waves and ancient analogues will be presented.

THE NATURE OF BED FORM MIGRATION IN SHALLOW MARINE ENVIRONMENTS: EVIDENCE FROM THE LOWER TRIAS, WESTERN ALPS, FRANCE

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Recent studies of intertidal and shallow subtidal bed forms have led to an increased understanding of the mechanics of bed form migration in tidal environments. These studies suggest that a careful examination of ancient tidal deposits in both a lateral and vertical sense may provide a better understanding of the variability of processes related to short (diurnal/semidiurnal) and long term (neap/spring) tidal cycles. How might these studies be extended to the interpretation of tidal structures observed in ancient shallow marine sequences? Within the Lower Trias of the Western Alps, France, tidal shelf deposits record the final stages of an Early Triassic marine transgression. The shelf sequences are dominated by cosets of cross-bedded quartz-arenite sandstone, separated by planar erosion surfaces overlying top-surface lags. Individual cross-sets, 0.15 to 1.47 m thick, show avalanche foresets composed of normally graded units of medium- to granule-grade grains. Sets are separated by reactivation surfaces spaced at intervals of 0.2 to 20 m. Between reactivation surfaces, graded foresets show a cyclic variation in thickness, grain size and angle of repose. The graded foresets are considered to reflect the avalanching of sediment previously sorted by smaller bed forms (ripples or megaripples) superimposed on the stoss side of a major bed form structure (megaripples or sand waves). The variation in foreset inclination is interpreted as the passive, active and static stages of bed form development, whilst the cyclicity in thickness and grain size of individual graded foresets may reflect the changing scale of superimposed bed forms in response to long-term tidal flow unsteadiness. From calculations of sand wave migration rates, assuming shear velocities of present day tidal shelves, it appears that bed form migration within the Trias shelf system was a response to long term (greater than months) fluctuations in tidal current velocities, enhanced by storm processes.

THE FACIES COMPOSITION OF UNCONFORMABLE QUARTZ-ARENITE SAND BODIES: SIMPLE, OR INTERNALLY COMPLEX?

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The genesis of quartz-arenite sand bodies preserved above unconformities has recently been brought into question. Until now their interpretation has been regarded as simply transgressive, without a full appreciation of the variability of their facies associations and their environments of deposition. The lower Trias of the Western Alps, France, provides an excellent opportunity to document the origins of this type of sand body. The succession unconformably overlies Carboniferous/Permian cover rocks and Hercynian basement massifs. The succession comprises a laterally extensive quartz-arenite member of conglomerate and sandstone, transitionally overlain by a red bed member dominated by siltstone and mudstone. The lower part of the quartz-arenite member developed in response to a marine transgression involving the landward migration of beach, ephemeral inlet, and shoreface environments with the eventual stabilization of a tidal shelf in areas between the basement massifs. The upper part of the quartz-arenite member and overlying red beds reflects deposition of prograding mesotidal barrier islands backed by extensive tidal flats.
Additional complexity is introduced by topography on the unconformity in the vicinity of basement massifs. Where the quartz-arenite oversteps the basement, thicknesses are drastically reduced and certain facies associations are no longer preserved. The vertical and lateral facies composition of this example confirms the complex origin of quartz-arenite sand bodies developed above unconformities.

PREDICTION OF TIDES IN EPEIRIC SEAS WITH A NUMERICAL MODEL: THE CRETACEOUS SEAWAY OF NORTH AMERICA

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A numerical model of the tides in the North American Cretaceous seaway was designed and the lunar semidiurnal tide calculated for a variety of possible controlling parameters. The most important parameters are the bathymetry and boundary conditions. Separate runs were made for uniform-depth models of 100, 200 and 600 m in a completely closed basin. The largest response is for the 200 m depth, because of a resonance of the seaway at 211 m.
Additional runs were made for different combinations of tidal forcing, according to whether the tidal force acted directly on the seaway (independent tide) or indirectly, through the seaway's possible connection with the Arctic Ocean or Gulf of Mexico (co-oscillating tide). The co-oscillating tide from the Arctic Ocean was very small with respect to the independent tide. However, a co-oscillating tide from the Gulf of Mexico could have had a significant effect on the seaway. In contrast, if the Gulf of Mexico had not been tidally connected to the seaway, a radiation condition along the southern boundary would have been appropriate. This reduces the independent tide by about 20%.
A spectral analysis of unforced oscillations of the seaway shows closely spaced peaks throughout the diurnal and semidiurnal tide bands for a 200 m deep basin. This indicates the likelihood of a tidal resonance occurring in the seaway. These peaks in the frequency spectrum are more closely spaced for models with shallower depth.
The maximum tidal range for the most "realistic" case (independent tide with a radiation condition on the southern boundary and co-oscillating tide at the north) is 86 cm, and the maximum current speed is 10 cm/s.

SHELF SEDIMENTATION PATTERNS IN EARLY PALEOZOIC TENSIONAL FAILED ARMS, SOUTH AFRICA

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Paleozoic reconstructions of Gondwana show southern Africa and Antarctica juxtaposed, with the wedge-shaped Falkland Plateau intervening in the southwest, the lines of contact between them forming a triple junction. Linear belts of Paleozoic subsidence developed along these lines of incipient fracture. Regional sedimentation patterns in the Ordovician Cape basin reflect this tectonic control. In the southwestern Cape, bed-load-dominated streams terminated southward in fan deltas. The fan deltas were flanked by barriers with associated tidal flats and lagoons. Transgression by the mixed tide-and-wave-dominated shelf allowed gradual accumulation of 2000 m of quartzose sand. The succession is dominated by tabular and lenticular sandstone bodies with megasets as much as 20 m thick, showing complex internal organization of smaller structures. This facies is compared with the tidal sand ridges and sand waves of the North Sea. These tidal sand bodies formed parallel to the shoreline. Deposition was strongly influenced by storm processes. Reactivation of these tensional failed arms formed an elongate embayment in the east, the Natal embayment. There, fan delta systems built out into a macrotidal gulf, where powerful tidal currents fashioned channels and bars trending perpendicular to the shoreline in a pattern analogous to the modern Ord River delta. Whereas the coastline in the southwestern Cape was relatively straight and open, the funnel-like configuration of the eastern gulf was probably responsible for amplification of the tidal range.

Paleoecology

PALEOECOLOGICAL PARAMETERS FOR THE STUDY OF SHELF SANDS AND SANDSTONES

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Sediments of the inner and outer shelf may be distinguished by using fossils as indicators of different environments. Molluscan-dominated inner shelf and bryozoan/brachiopod-dominated outer shelf environments have been documented from Recent high-latitude seamounts, micro-continents and tectonically active shelves. These two belts may be extended back in time to Upper Paleozoic shelves, such as the Carboniferous of Kansas and the Devonian of New York State. Orientation and mode of preservation of shells is different in tide-dominated and storm-wave dominated settings. Resistate carbonate fractions are often dominated by serpulids in Recent tidal sand wave complexes and dominated by serpulids, belemnite guards and brachiopods in the Mesozoic. Storms, by contrast, may cause only one reworking event and shells may be well preserved. Benthic communities may be related to bed shear stress: the bivalves *Modiolus* and *Glycymeris* are typical of tide-dominated settings. Dead shells rarely move more than 5 km before becoming reduced to unrecognizable bioclastic carbonate. Shell debris from high-energy environments has few borings, whereas low-energy environments are characterized by much boring. Regional mapping of calcareous algae, algal borings and associated limpet grazing traces enables the photic zone to be determined. In the tropics the entire shelf (up to 200 m depth) may fall within the photic zone but high-latitude shelves have a photic limit of 30 to 40 m. This method has successfully indicated the depth of deposition of Lower Cretaceous shales from the North Sea Basin.

BODY FOSSILS OF TIDE- AND WAVE-DOMINATED CONTINENTAL SHELVES

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Important evidence on the provenance of sandstones can come from the study of their associated faunas. Analysis of the sediments and faunas of the offshore tidal sand sheet and sand bank facies on the tidal-current-dominated northwest European continental shelf has demonstrated several criteria that should be widely applicable to paleoenvironmental studies of sandstone successions and to basin analysis. The bed forms that are present in the sand sheet facies and which are related to decreasing tidal-current strength are furrows, sand ribbons, large and small sand waves, small sand waves alone, rippled sands and sand patches. Each bed form supports a characteristic fauna of potential body fossils consisting mostly of molluscs, echinoderms and crustaceans. Potential trace fossils are provided by polychaetes, echinoderms and other groups. Sand ribbons are unlikely to be preserved, but the underlying and adjacent gravel floor supports a moderately diverse fauna, which could be preserved. Large sand waves (with small sand waves on them) support a low diversity fauna comprising few individuals with low preservation potential. Diversity is greatest in the zone of rippled sand and its associated gravel sheet, and the preservation potential is much higher. Evidence currently available suggests that differentiation between active sand banks with sand waves on them and active sand wave fields is difficult if only faunal criteria are used. Bed forms on wave-dominated shelves are generally much more uniform and are broadly analogous to the rippled sand zone. By analogy, these wave-dominated sand sheets support a diverse fauna of both body and trace fossils with high preservation potential. Detailed studies are required to identify geologically significant differences between faunas of wave-dominated sand sheets and those of tidal-current-dominated rippled sands. The effects of storm-generated waves on the faunas of both tidal and wave-dominated shelves can be catastrophic and could therefore increase the preservation potential of both faunas. The leaching of body fossils in such sandstones during diagenesis causes additional problems, which must be taken into consideration.